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CRITICAL MASS STUDIES, PART X

Uranium of Intermediate Enrichment

D. F. Cronin

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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Neutron Physics Division

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ABSTRACT

Critical mass studies intended primarily to establish nuclear safety criteria for handling and processing enriched uranium have been made with material enriched to 4.89 and 37.5% in the U^{235} isotope. Uranium oxide (U_3O_8), uranyl fluoride (UO_2F_2), and uranium tetrafluoride (UF_4) were chosen as the principal experimental materials and they were mixed with hydrogenous compounds over a wide range of concentrations. Both water-reflected and unreflected assemblies were constructed.

Water reflected assemblies of the 4.89%-U^{235}-enriched uranium gave 3.05 kg of U^{235} as the minimum critical mass for U_3O_8 moderated with glycerol tristearate. At the same enrichment, but with aqueous solutions of UO_2F_2 at a higher uranium density, a minimum critical value of 1.9 kg of U^{235} was obtained. Removal of the water reflector increased these values to 5.0 kg for the U_3O_8 system, and 2.4 kg for the UO_2F_2 solution.

The critical mass of a water reflected cube of a UF_4-CF_2 mixture, with the uranium enriched to 37.5% in U^{235} and a density of 4.8 g/cc, was 183.8 kg of U^{235}. Removal of the water reflector increased this mass to 491.8 kg U^{235}. Critical parameters were evaluated at other moderations up to and including an H:U^{235} atomic ratio of 17.

The average U^{235} enrichment in another series of experiments was adjusted to intermediate values by grossly latticing blocks of 0.2 and 37.5% enrichment. The resulting inhomogeneity, aggravated by the simultaneous heterogeneity of internal moderator, makes the results difficult to interpret.

Relative neutron flux measurements, with various detectors, were made on a number of the systems. Also reported are comparisions of the effect of air and of water separating the components of reflected critical assemblies.

ACKNOWLEDGEMENT

Grateful acknowledgement must be made for the active cooperation and valuable assistance of the entire staff of the Critical Experiments Facility during the period (1951 to 1957) over which these data were obtained. Particular recognition is due to L. W. Gilley, J. T. Thomas, and D. W. Magnuson for their contributions to this program, with special appreciation for the assistance of Dixon Callihan both in the experimental work and in the preparation of this report.

Table of Contents

Table of Contents, Cont'd

INTRODUCTION

The critical experiments reported here are a continuation of a series of critical mass studies begun in 1946 which are intended to establish nuclear safety criteria for the handling and processing of enriched uranium. In the present work data have been obtained principally from assemblies containing uranium enriched to 4.89 and 37.5 wt% in the U^{235} isotope. Some additional information describes grossly heterogeneous assemblies containing uranium at average enrichments of 12.5, 18.8, 25, and 30 wt%. The 4.89 wt% enrichment was studied in both solid and liquid homogeneous systems; the 37.5 wt% enrichment was studied both as an unmoderated assembly of small blocks made of a mixture of UF_4 and Teflon $(CF_2)_n$, and as a heterogeneously moderated assembly of the blocks. The intermediate enrichments were simulated by lattices of dimensionally and chemically identical blocks made from uranium containing either 0.2 wt% U^{235} or 37.5 wt% U^{235}. These assemblies were also both unmoderated and heterogeneously moderated with an hydrogenous plastic.

As in previous work, the experiments consisted in assembling sufficient fissionable material either to sustain a nuclear chain reaction, or to attempt an estimation of the critical parameters by an extrapolation of the source neutron multiplication. Critical masses and volumes of parallelepipeds, cylinders, and spheres, both with and without an hydrogenous neutron reflector, have been obtained over a wide range of neutron moderation. The data, including those describing flux distributions and the effects of partial reflection, have been tabulated in the appendices.

I - EXPERIMENTAL MATERIALS

Uranium of three degrees of enrichment (0.2, 4.89, and 37.5 wt% U^{235}) was the source material for these measurements. The 4.89 wt% material was first utilized as U_3O_8, and later as soluble uranium oxyfluoride, UO_2F_2, while the 0.2 and 37.5 wt% materials were prepared as uranium tetrafluoride, UF_4, for experimental use. The specific utilizations are described in detail below, while chemical and spectrographic analyses of the material are given in Tables A-1, A-2, A-3, A-4, and A-7, pages 39, 40, and 42.

U_3O_8 Mixtures

Uranium oxide, U_3O_8, was mixed with Sterotex, glycerol tristearate, in the proportions shown in Table A-5 to obtain $H:U^{235}$ atomic ratios from essentially zero to 757. Since the density of hydrogen in Sterotex, $(C_{17}H_{35}COO)_3C_3H_5$, is approximately that of water, a moist accumulation of oxide was simulated by the mixture. Approximately 600 kg of U_3O_8 (25 kg of U^{235}) were available.

The U_3O_8-Sterotex mixtures were packaged in 1/16-in.-thick wall, type 3S aluminum boxes, shown in Fig. 1, with outside dimensions of 8 x 8 x 8 in., 8 x 8 x 4 in., and 4 x 4 x 4 in. (Smaller boxes would have resulted in

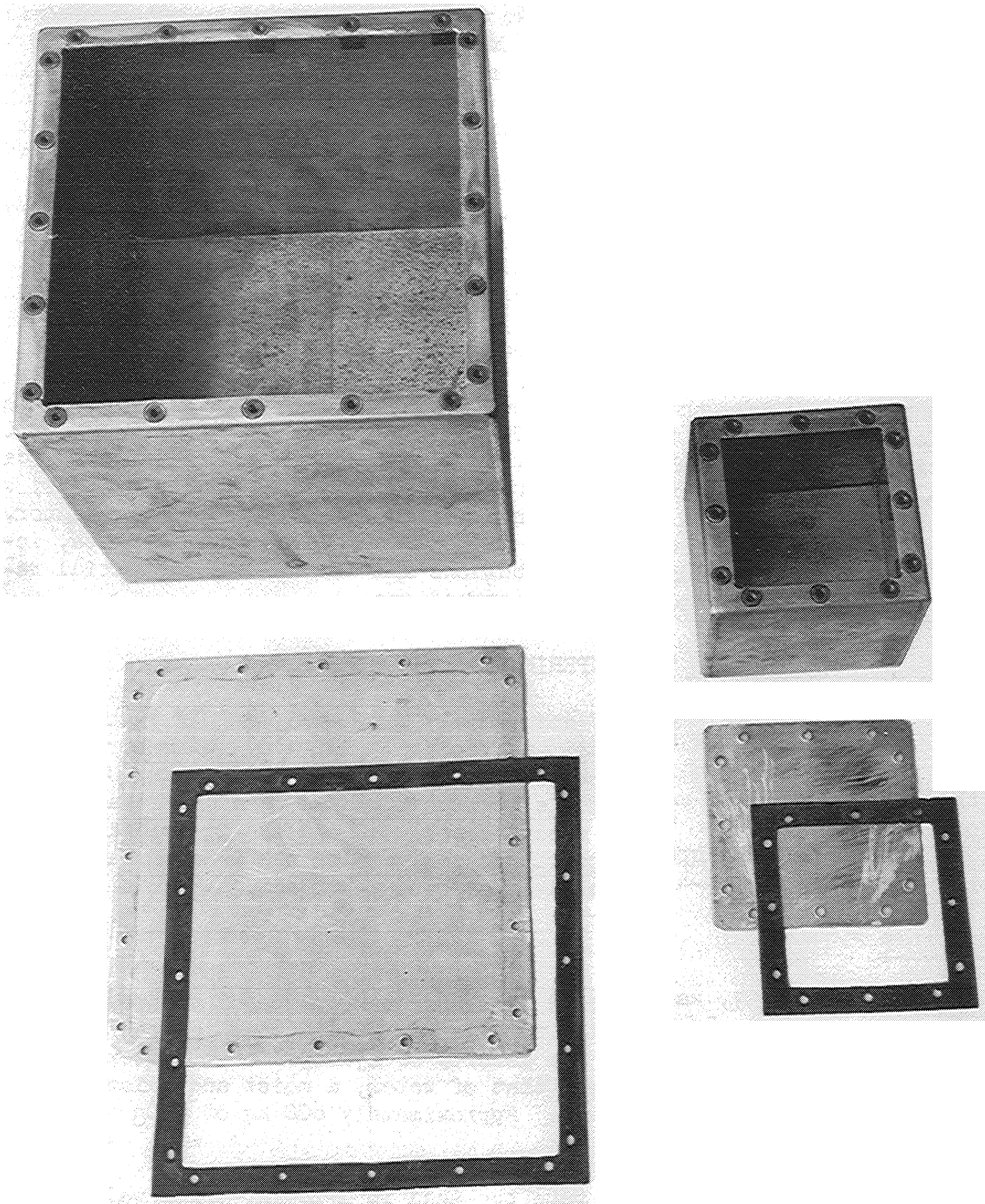

Fig. 1. Photograph of Disassembled Boxes Used to Contain U_3O_8-Sterotex Mixtures.

excessive aluminum-to-uranium mass ratios, while larger ones would have been difficult to handle.) The covers of the boxes were attached by brass screws and inserts, against a 1/32-in.-thick, 1/4-in.-wide rubber gasket. The total volume of brass was 20 cm^3 for the largest boxes, and 12 cm^3 for the smallest.

Unavoidable variations in density among the several boxes of U_3O_8-Sterotex mixture were evaluated in a few independent experiments by interchanging boxes of varying density within the same assembly, and it was determined that such variations had only a small effect on the critical mass, ranging from ~0.6% for low moderations to ~1% for high moderations.

UO_2F_2 Solutions

UO_2F_2 prepared from the U_3O_8 mentioned above was dissolved in water containing $<$ 2ppm detectable metallic impurities to obtain solutions of $H:U^{235}$ atomic ratios from 524 to 1099 (Table A-6). The lower limit, 524, is very nearly the maximum solubility of UO_2F_2 in water at 25°C (870 g of U per liter). About 150 kg of uranium (7.55 kg of U^{235}) were prepared for these experiments. Test vessels, having a wall thickness of 1/16 in., were fabricated from type 316 or 347 stainless steel, and from type 2S or 3S aluminum, the latter being protected from the solution by a baked-on phenolic enamel.

UF_4-CF_2 Mixtures

Equimolar quantities of finely ground UF_4 and CF_2 were intimately mixed and cold pressed at a pressure of 50 tons per $in.^2$ to obtain rectangular blocks having a density of 4.78 g/cm^3. Visual differential between blocks pressed from the 37.5 wt% U^{235}-enriched UF_4 and those pressed from the 0.2 wt% U^{235} (99.8 wt% U^{238}) material was effected by adding 1% by weight of carbon flour to the latter.

Combinations of both types of blocks in varying proportions enabled simulation of enrichments intermediate between 0.2 and 37.5 wt% U^{235}. Moderation of assemblies of these blocks was accomplished by sheets of a methacrylate plastic ($C_5H_8O_2$) from 1/8- to 3/4-in.-thick having a hydrogen density (0.10 g/cm^3) very nearly that of water (0.11 g/cm^3).* These sheets were interleaved among the UF_4-CF_2 blocks. It must be emphasized that this method did not produce a homogeneous distribution of moderator.

Density Considerations

The critical mass of a mixture or solution of uranium is a function of the U^{235} density. The density, in turn, depends upon the density of the uranium material, and, to a lesser extent, upon the density of the

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* A single experiment was performed in which sheets of 0.01-in.-thick cellulose acetate ($C_{10}H_{18}O_5$) was used as moderator.

solvent or the diluent material. Although the uranium concentration (mass per unit volume) and the neutron moderation (H:U atomic ratio) are mutually dependent in an aqueous solution of a uranium salt, such is not the case with mixtures of particulates of uranium or uranium compounds with other materials. For example, a suspension of uranium sawdust in oil might have a decidedly higher uranium density than would a fluffy uranium compound mixed with an organic powder, even though both mixtures have the same hydrogen-to-uranium ratio. Since the primary purpose of this work was to extend criteria for uranium processing, density considerations have been emphasized.

Figure 2 displays the densities of both the UO_2F_2 solutions and U_3O_8-Sterotex mixtures used in these experiments, plotted as a function of the $H:U^{235}$ atomic ratio. It is evident that, in the region of overlap, the solutions have a higher density than the oxide-organic mixtures causing, as will be shown later, significant differences in critical parameters at the same moderation. The third curve, identified as from the Oak Ridge Gaseous Diffusion Plant "solubility data," summarizes some unpublished measurements on various mixtures of salts and hydrogenous liquids, such as UF_4 + HF, UO_2F_2 + H_2O, etc., in proportions well beyond the limits of solubility. Such mixtures are representative of the slurries, precipitates. etc., which might be encountered in chemical processes. Since it is evident that the UO_2F_2 solution closely approaches these conditions, while the oxide-Sterotex mixtures have much lower densities, the data from the oxide-Sterotex experiments, which permitted a much greater range of moderation, have been used to guide extrapolations of the solution data to minimum critical masses and volumes.

The hydrogen density of both the U_3O_8-Sterotex mixtures and the UO_2F_2 solutions is plotted as a function of $H:U^{235}$ atomic ratio in Fig. 3.

II - INSTRUMENTATION AND SAFETY DEVICES

Conventional instrumentation employed for these measurements included, for each experiment, a minimum of three BF_3 ionization chambers and two boron-lined proportional counters for neutron monitoring, and two gamma-ray detectors. Supplemental instrumentation was employed as required.

Each test assembly was provided with appropriate "fail-safe" safety devices, which were actuated either by signal of a monitoring instrument or by power interruption. The basic shutdown mechanism was fuel removal, augmented in certain cases by rapid insertion of a neutron absorber into the system.

A Po-Be source of $\sim 10^6$ n/sec, placed close to the test assembly, was used during subcritical measurements, being withdrawn into a shielded container at criticality. It was found after preliminary experiments that

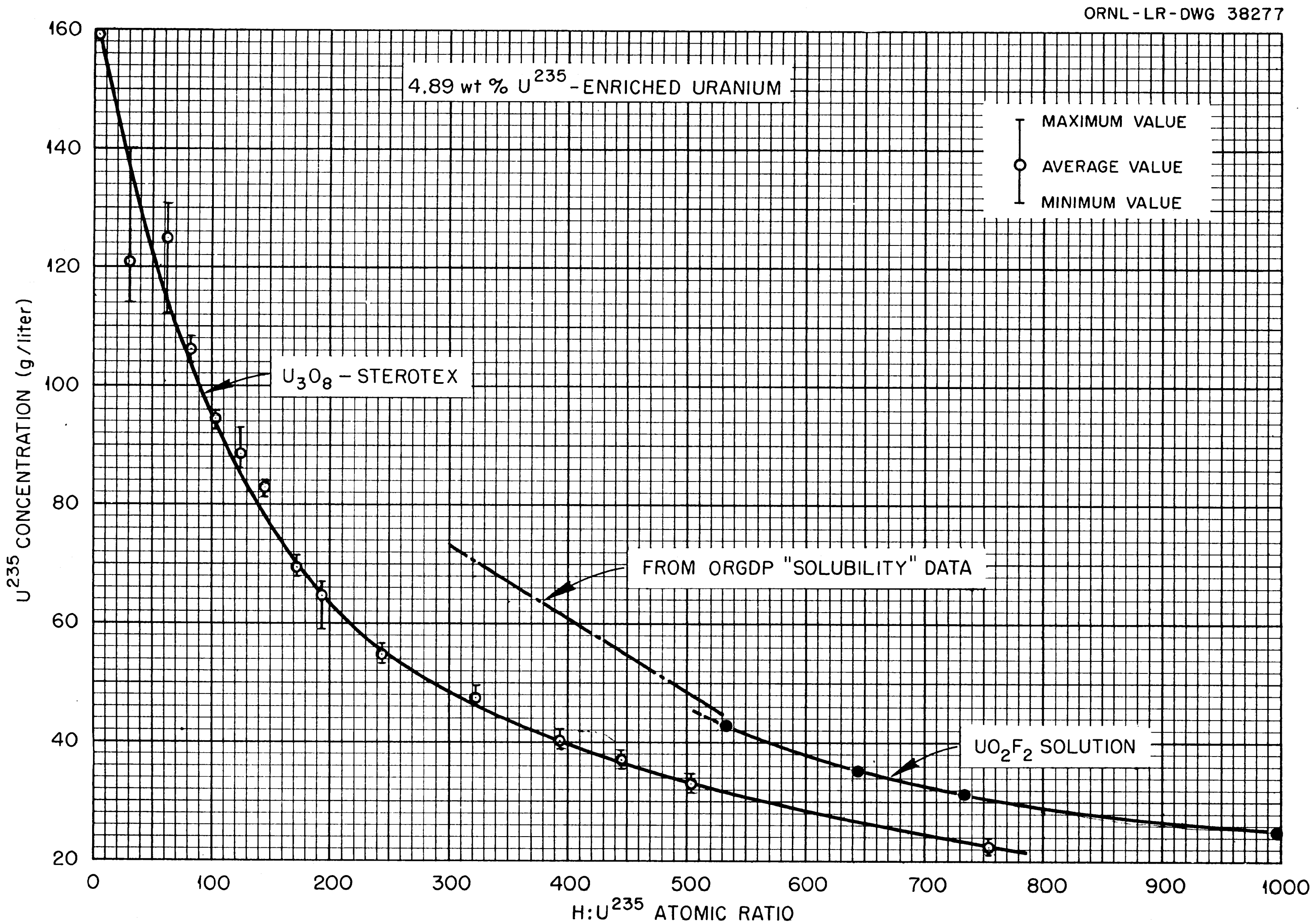

Fig. 2. Relative U^{235} Densities of UO_2F_2 Solutions and U_3O_8–Sterotex Mixtures.

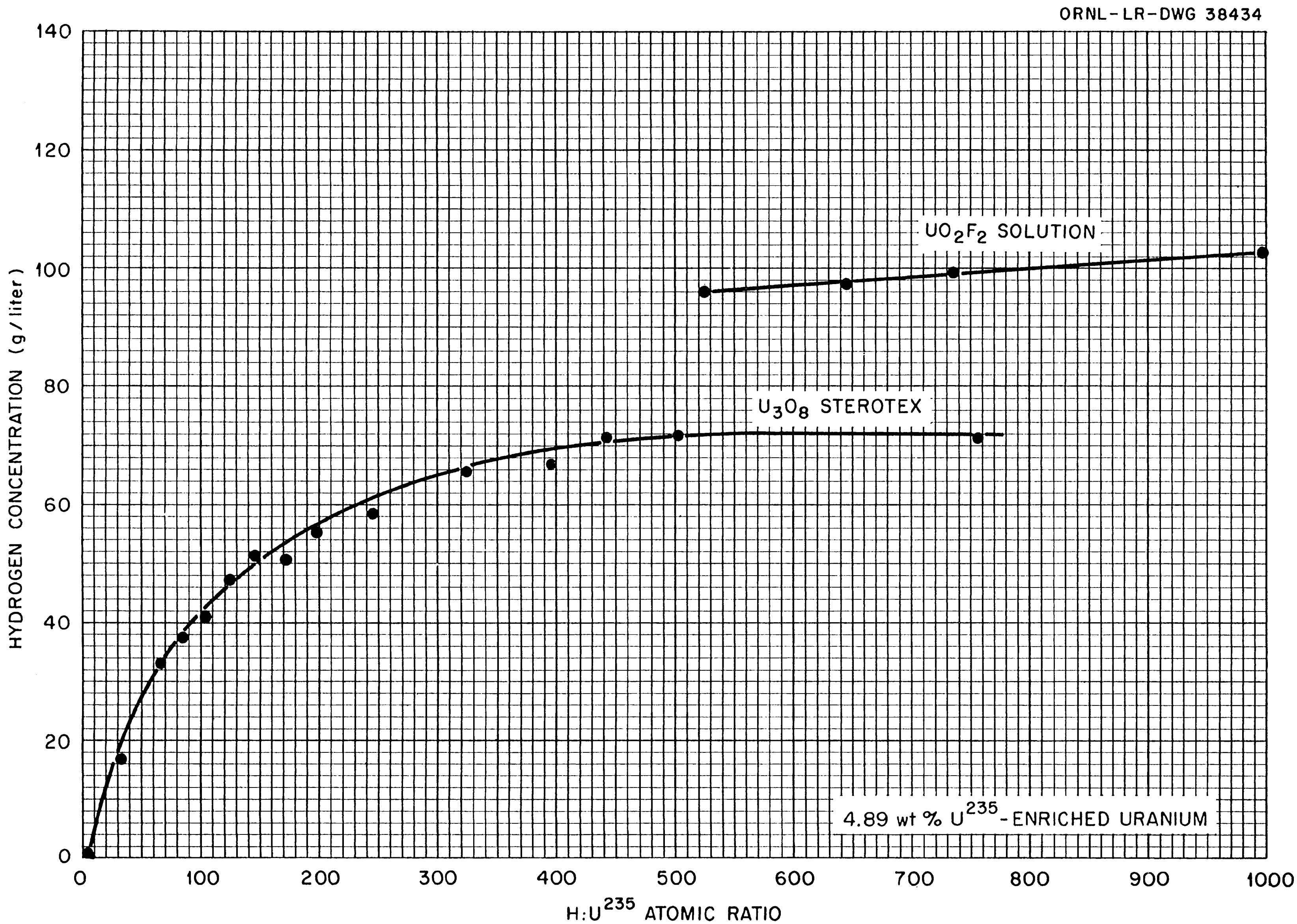

Fig. 3. Hydrogen Density as a Function of H:U^{235} Atomic Ratio.

such an external neutron source was not needed with the UF_4-CF_2 blocks of 37.5% enrichment since sufficient neutrons were generated internally, probably from the (α,n) reaction with the fluorine, to be effective.

III - EXPERIMENTAL APPARATUS AND PROCEDURES

Solid Systems

No External Reflector - All unreflected solid systems, whether U_3O_8 in cans or UF_4-CF_2 blocks, were built upon the separate parts of a divided aluminum table, shown in Fig. 4, which could be brought together by a remotely operated, magnetically coupled screw jack to form the test assembly. The separation of the table parts was monitored to within 0.10 in. by a selsyn receiver in the control room, and, additionally, to within ± 0.010 in. during the final inch of approach by visual observation of a dial micrometer attached to the fixed part of the table. A scram signal initiated by the safety devices caused the magnetic coupling to be de-energized, allowing the parts of the table to be rapidly separated by either counterweights or by an air cylinder.

External Water Reflector - Water-reflected assemblies were constructed upon a 4 x 4 x 1 ft Lucite table located within a 6 ft square tank (Fig 5a). The remotely controlled addition of water reflector was observed directly on a calibrated sight glass in the control room. While assemblies of the water-tight U_3O_8 containers were placed directly in the water, the UF_4-CF_2 assemblies were protected from water damage by a 1/16-in.-wall rubber sack (Fig. 5b). A 6-in.-thick layer of paraffin was used as a top reflector. Safety devices consisted of magnetically supported cadmium sheets arranged to drop between the water reflector and the test assembly.

Aqueous Solution Systems

The procedure for the measurement with UO_2F_2 solutions followed that of earlier solution work. The test vessels were supported in a 9-ft-dia cylindrical steel tank which could be filled with water to provide an effectively infinite neutron reflector. A water-filled container which could be adjusted to contact the UO_2F_2 solution surface acted as a top reflector. Access tubes for safety and control devices extended through this container. Solution height and top reflector position could be determined to within ± 0.01 in. Test vessels were designed with a 3-in.-dia solution feed section which supported the vessel at least 12 in. above the floor of the reflector tank. The neutron source employed for subcritical measurements was contained within a small re-entrant tube concentric with the feed section, and at criticality was withdrawn into a shielded container.

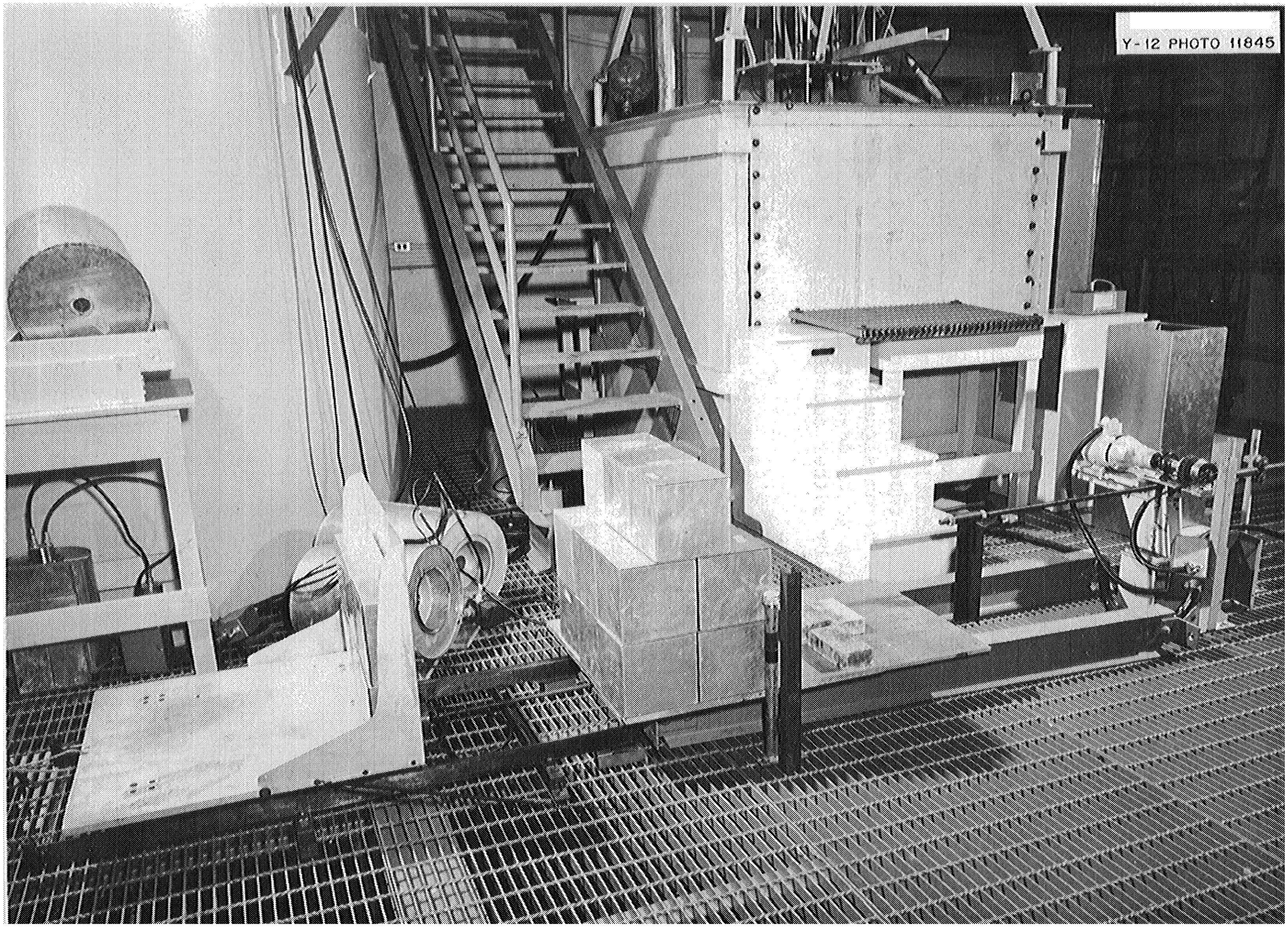

FIG. 4

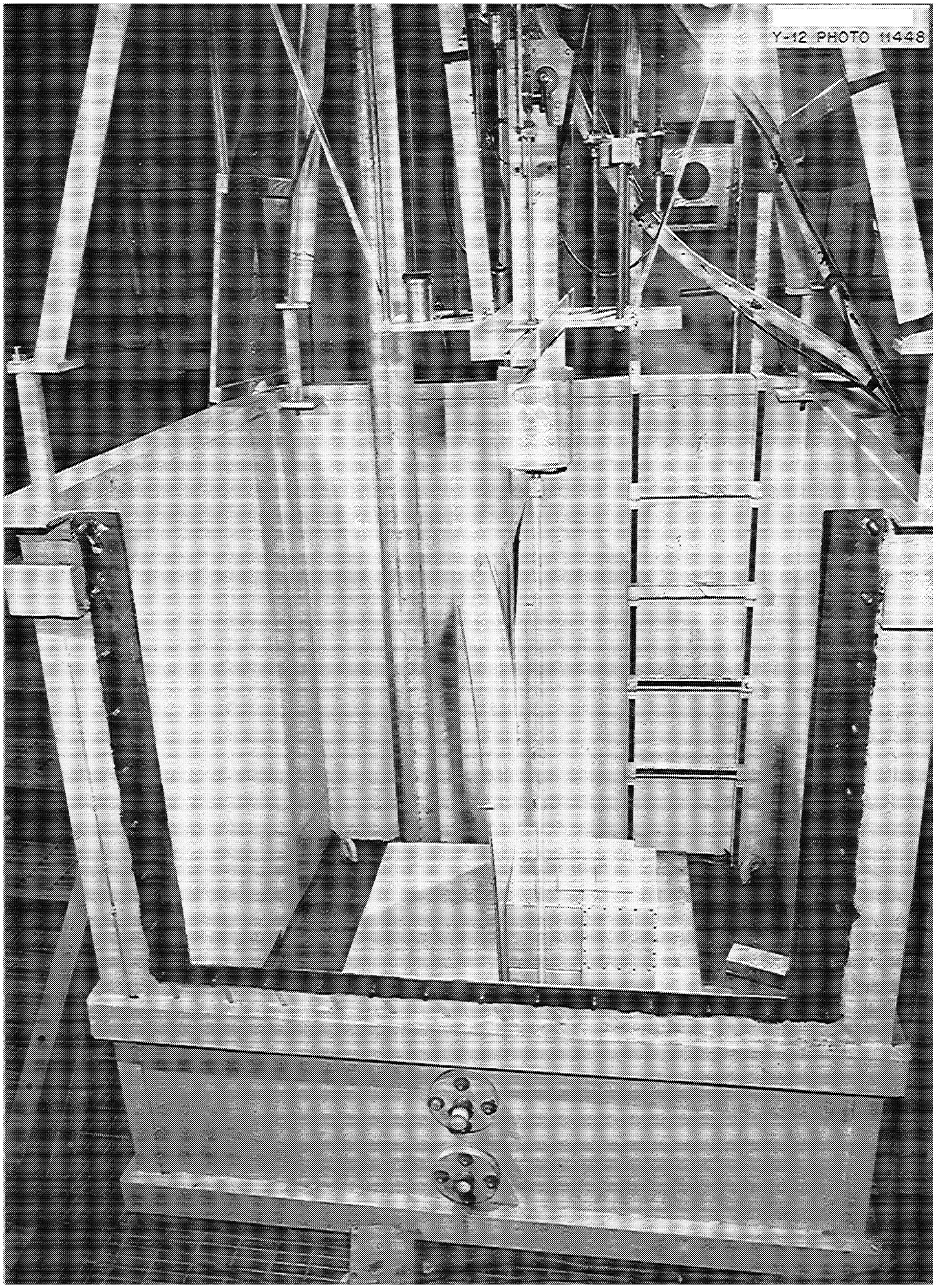

FIG. 5a

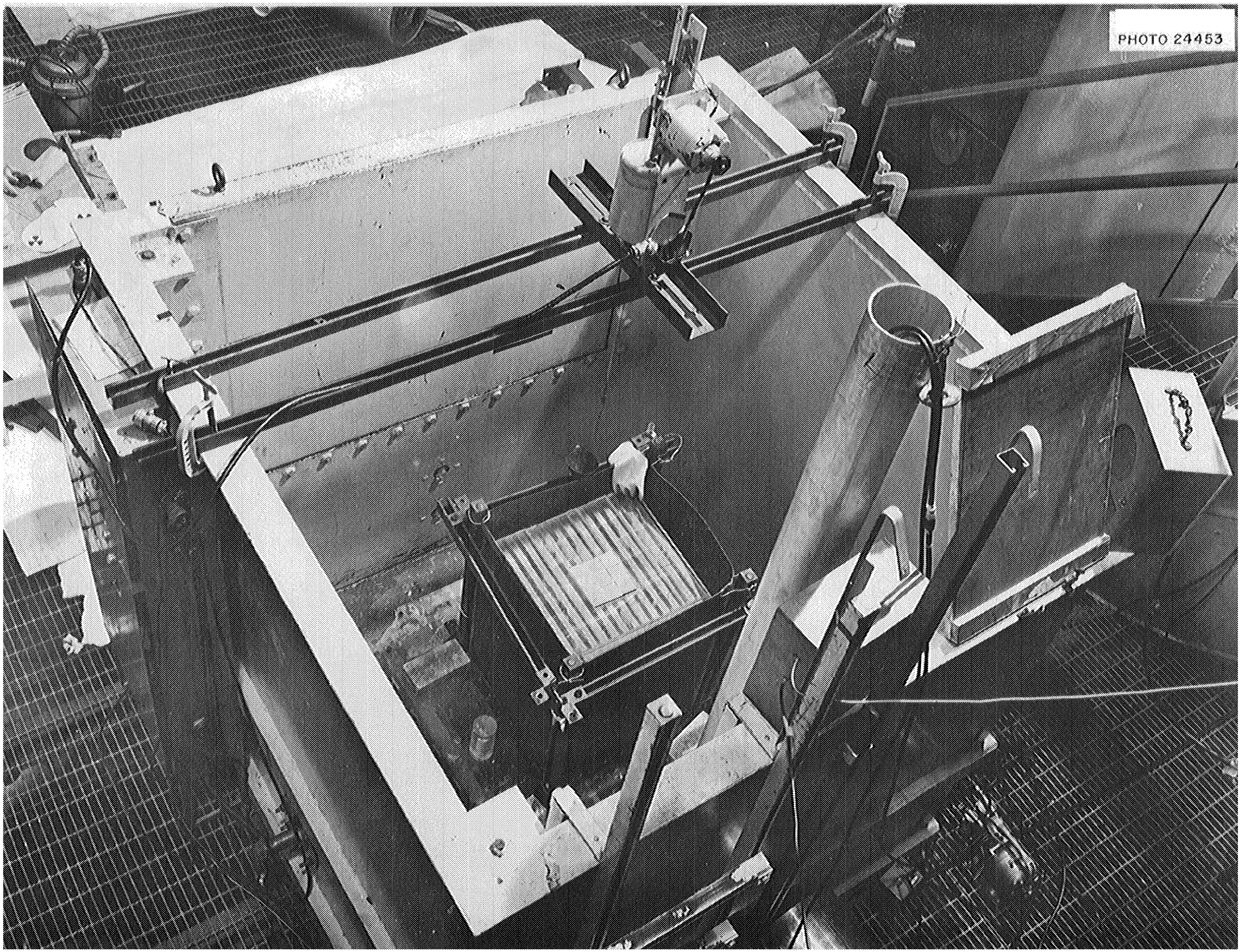

FIG. 5b

IV - EXPERIMENTAL RESULTS

The results of this work describe primarily the critical mass and critical dimensions of many arrays of the several experimental materials. The overall composition of these arrays, their shape, and the neutron reflector conditions are the principle variables. These results are summarized in this section of the report and the measurements themselves are recorded in the appendices. These data were generated during intervals between 1951 and 1957 and some have been made known to a few interested personnel through documents of limited distribution[1,2,3,4] and through personal communications. The data from unreflected arrays of 37.5%-U^{235}-enriched uranium and from assemblies of average enrichment between 12 and 30% are reported here for the first time.

U_3O_8-Sterotex Mixtures (4.89 wt% U^{235}-Enriched Uranium)

Water-Reflected Systems - Because of the limited quantity of U^{235} available for these experiments, approximately cubical water-reflected assemblies with $H:U^{235}$ atomic ratios less than $\sim$ 75 were subcritical, although some estimates of critical parameters were possible by extrapolation of source neutron multiplication data. Other assemblies of materials near the optimum concentration were subcritical because of their shape. Data from all subcritical assemblies are given in Table B-1, page 44.

Table B-2 lists the data obtained from critical assemblies with $H:U^{235}$ atomic ratios ranging from 63.7 to 756.6, while minimum masses and volumes for these systems are plotted as functions of the $H:U^{235}$ ratio in Figs. 6 and 7. Since the unit of material was 4 x 4 x 4 in., it was not possible to assemble a critical system as an exact cube. The dimensions of a critical assembly were, therefore, obtained by an interpolation between two assemblies, one subcritical and the other supercritical, differing only by one unit, usually placed on top of the stack. The effective height was computed by evenly distributing the increment over the horizontal area of the assembly. From Figs. 6 and 7 the minimum critical volume ($\sim$ 80 liters) occurs at an $H:U^{235}$ atomic ratio of $\sim$ 325, the minimum critical mass ($\sim$ 3.5 kg) at an $H:U^{235}$ ratio of $\sim$ 450.

Unreflected Systems - Table B-2, page 45, and Figs. 6 and 7 display the results from a few essentially cubical unreflected U_3O_8-Sterotex

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1. D. Callihan and D. F. Cronin, Ring Tamping, Y-B23-22, Nov. 5, 1952.
2. D. Callihan, Summary of Critical Experiments with 4.9 Percent Enriched Uranium, GEH-22802, Nov. 30, 1953.
3. D. F. Cronin, J. T. Thomas, Physics Division Semi-Annual Progress Report for Period Ending March 10, 1955, ORNL-1926, p. 7.
4. D. Callihan and D. F. Cronin, Critical Experiments with Uranium of Intermediate U^{235} Content, ORNL CF 55-10-97, Oct. 21, 1955

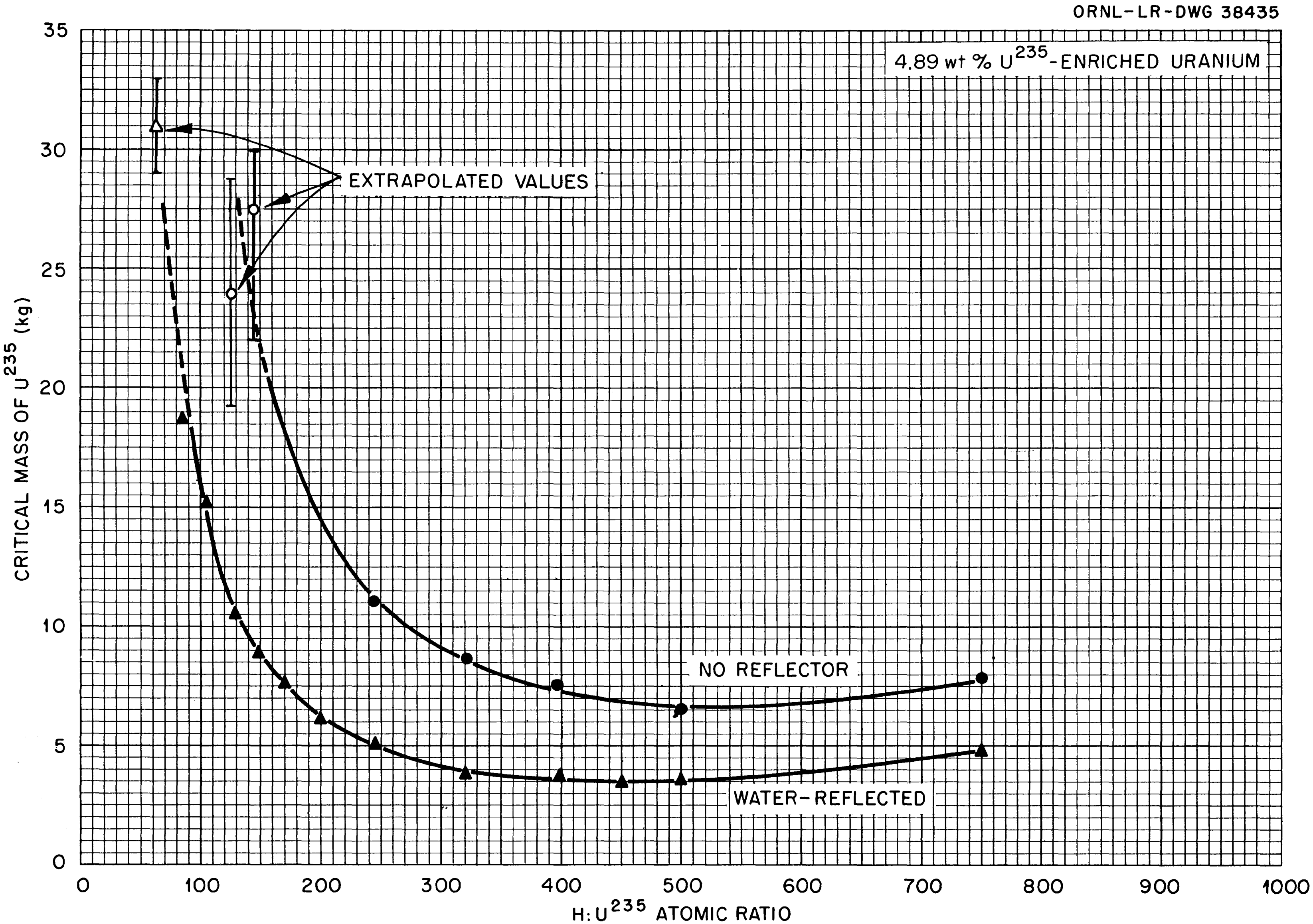

Fig. 6. Lowest Experimental Critical Mass of U_3O_8 – Sterotex Mixtures as a Function of H:U^{235} Atomic Ratio.

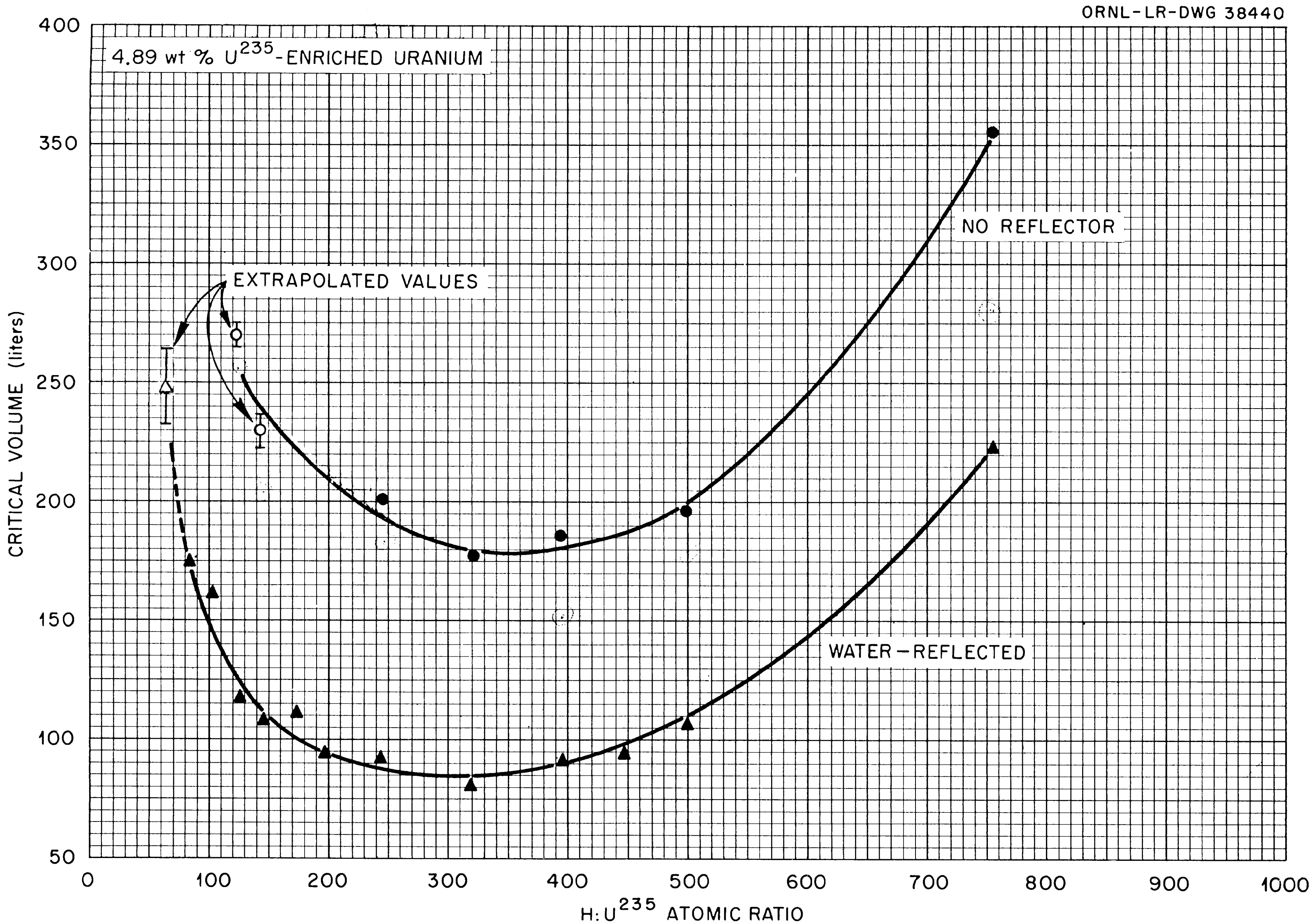

Fig. 7. Lowest Experimental Critical Volumes of U_3O_8 – Sterotex Mixtures as a Function of H:U^{235} Atomic Ratio.

assemblies. The minimum critical volume and minimum critical mass appear to exist at approximately the same moderation ratios as with the reflected assemblies.

UO_2F_2 Solutions (4.89 wt% U^{235}-Enriched Uranium)

The critical parameters of both water-reflected and nominally unreflected UO_2F_2 solutions contained in cylinders, a parallelepiped, and a sphere, are given in Table B-3 for H:U^{235} atomic ratios from 524 to 1099. These data have been corrected for the effect of the 3-in.-dia feed section. Figure 8 presents the critical masses, and Fig. 9 shows the critical volumes, both plotted as functions of the H:U^{235} atomic ratio. The values plotted are the lowest experimental masses and volumes observed at each particular concentration, and no attempt has been made to extrapolate the curves to lower moderations. The same data, but with critical height plotted as a function of cylinder diameter for constant H:U^{235} ratios, are shown in Fig. 10.

UF_4-CF_2 Mixtures (37.5 wt% U^{235}-Enriched Uranium)

Unreflected Systems - Assemblies composed of the 37.5 wt% U^{235}-enriched UF_4-CF_2 blocks were constructed with H:U^{235} atomic ratios ranging from 0.07 (the residual moisture remaining in the block after fabrication) to 17. The effect of the 1-in.-thick aluminum base plate, upon which these materials were assembled, was evaluated by placing a similar sheet of aluminum on the top of various assemblies and appropriate corrections were made to the observed critical masses. As shown in Table B-4 this effect was greatest at low H:U^{235} atomic ratios.

An essentially unreflected and unmoderated cubical assembly of the available UF_4-CF_2 blocks (467 kg of U^{235}) was subcritical. Extrapolation of the source neutron multiplication data from this assembly, however, indicated that a cube 29.2 in. on an edge, containing 482 kg of U^{235} would be critical. This result was in good agreement with data obtained from the pseudo-cylinder shown in cross section in Fig. 11 which, with a base area equivalent to a 32.84-in.-dia cylinder, was critical when 28 in. high. Extrapolating the dimensions of this cylinder by equating bucklings and using an extrapolation distance of 0.80 in., an average from flux distribution measurements, yielded 29.4 in. as the dimensions of a critical cube and 16.6 in. as the radius of a sphere.

The pseudo-cylinder was also used in a supplementary experiment designed to evaluate the reactivity effect of various reflecting materials placed against one of the flat lateral surfaces of the cylinder. The measurement was based upon the observation that the reactivity of the pseudo-cylinder varied linearly with separation distances between sections from 0.20 to 0.80 in., with an average value of $2.77 per inch over this range. The change in separation required to maintain criticality when a reflector material was placed against the cylinder was thus a measure of the change in reactivity caused by the reflector. Since the change in

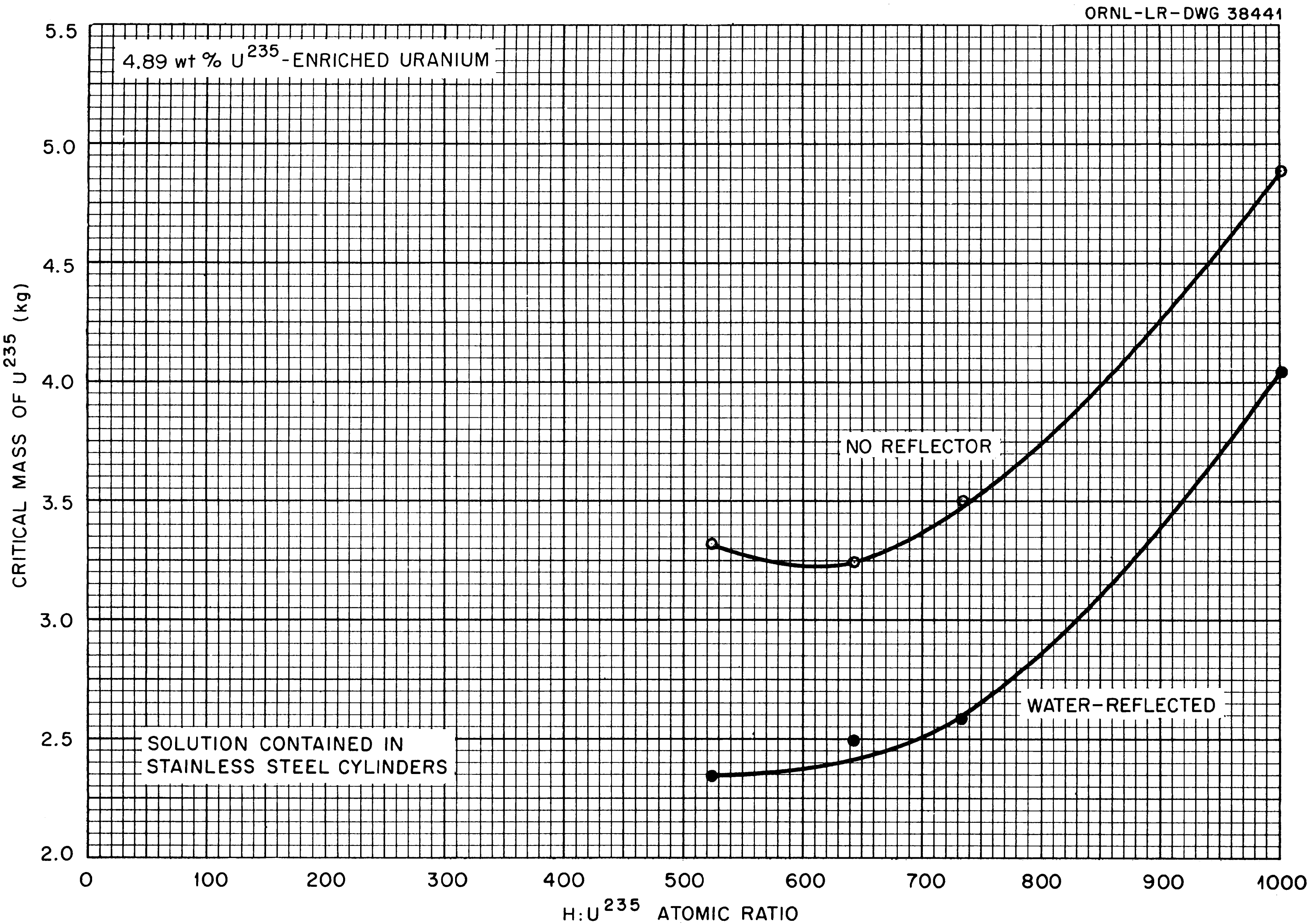

Fig. 8. Lowest Experimental Critical Mass of UO_2F_2 Solution as a Function of $H:U^{235}$ Atomic Ratio.

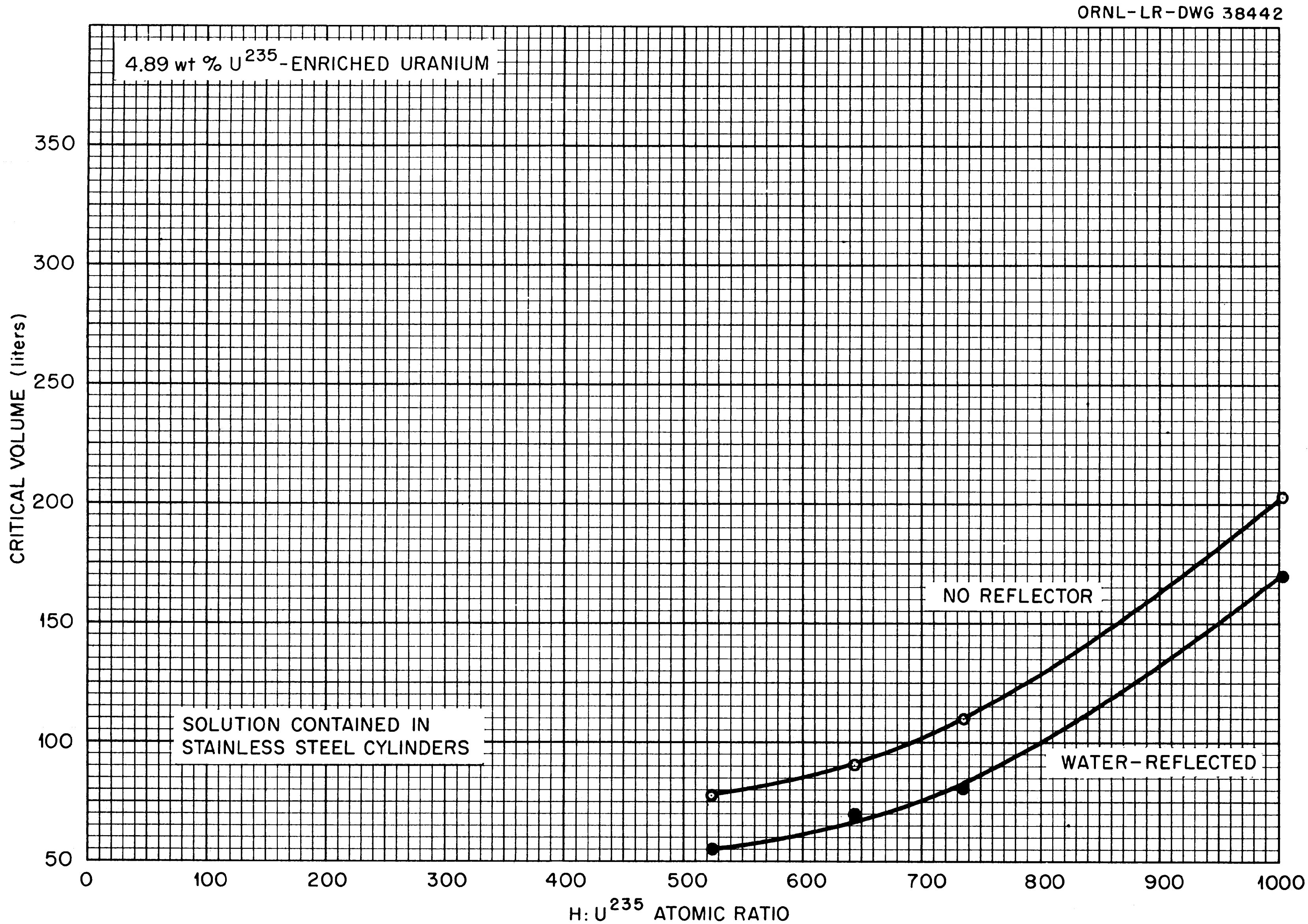

Fig. 9. Lowest Experimental Critical Volume of UO_2F_2 Solution as a Function of $H:U^{235}$ Atomic Ratio.

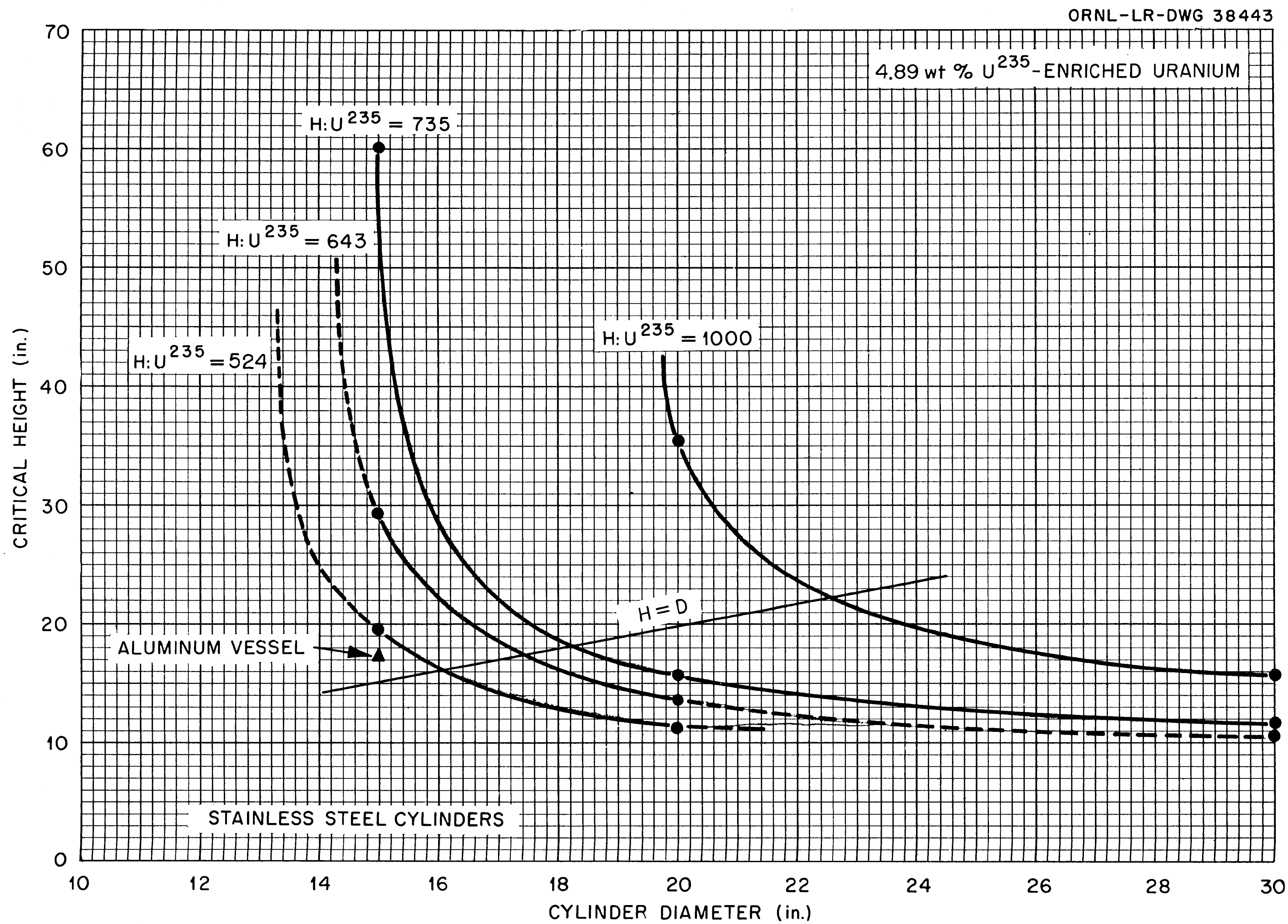

Fig. 10. Critical Height of UO_2F_2 Solution as a Function of Cylinder Diameter.

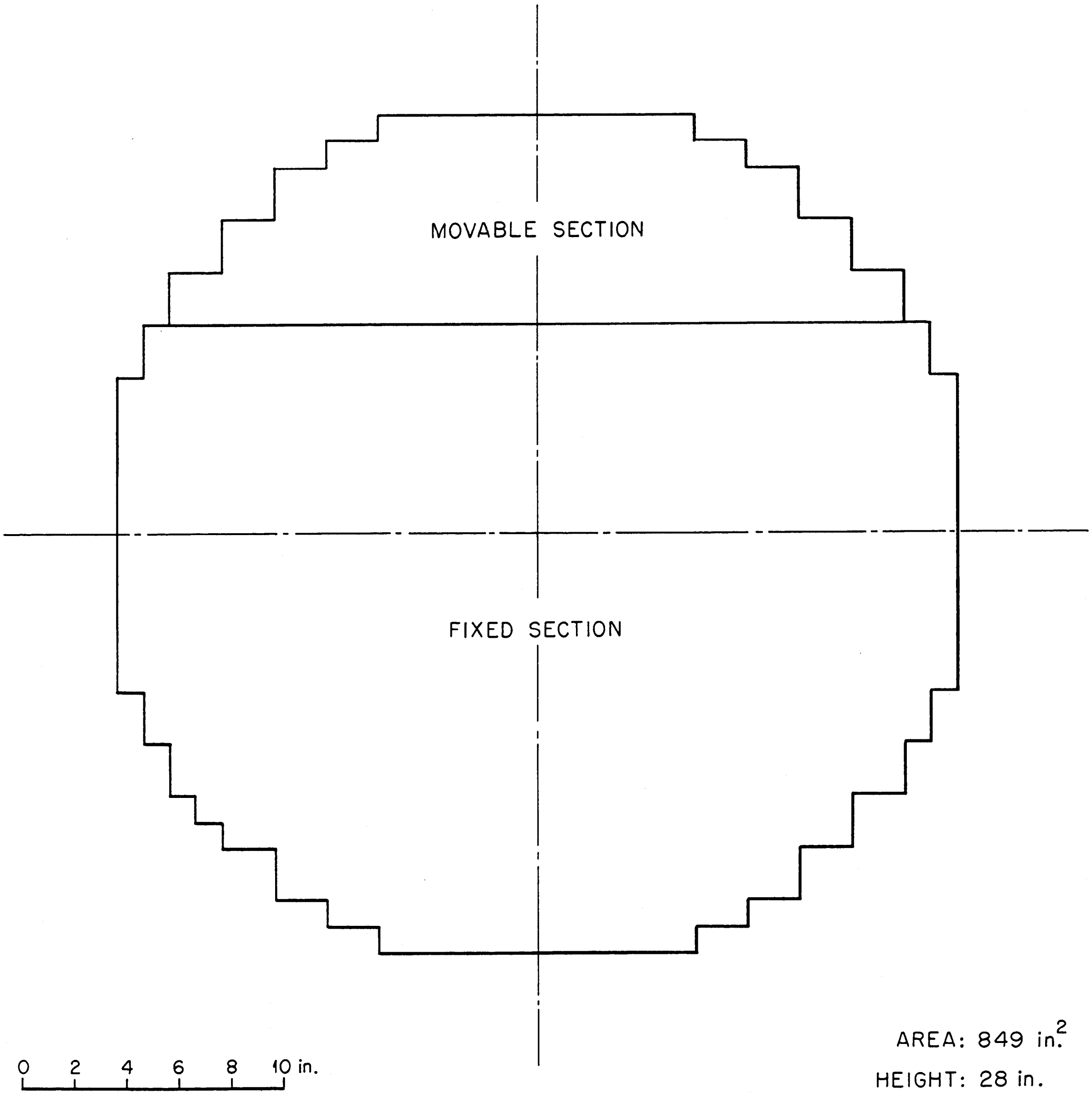

Fig. 11. Cross Section of the "Pseudo-Cylinder" Critical Assembly. The assembly was constructed of 37.5 wt % U^{235}-enriched uranium as UF_4-CF_2 mixture, without moderator or reflector.

reactivity was linear only over a limited separation distance, the table position was maintained within these limits by removing suitable amounts of fuel from the movable portion. The data are plotted in Fig. 12 and tabulated in Table B-5.

Variation of the $H:U^{235}$ atomic ratio in the block assemblies was accomplished by insertion of plastic sheets between the blocks. A 0.010-in.-thick cellulose acetate layer, for example, increased the $H:U^{235}$ atomic ratio to 0.165, decreasing the critical mass of the cube to 467.9 kg of U^{235}. The effect of this method of moderation, which obviously gives a lattice of moderating material rather than an homogeneous distribution, was evaluated in four experiments. In these experiments, as shown in Table B-4, the $H:U^{235}$ atomic ratio was approximately constant (~ 4.8) but the thickness of the interleaved plastic was varied from 1/4 to 1-1/2 in. The unavoidable small differences in the $H:U^{235}$ ratio were corrected for by using the slope (28 kg per $H:U^{235}$ unit) of the critical mass vs $H:U^{235}$ ratio curve shown as Fig. 13 for $H:U^{235} = 4.82$. The adjusted data, plotted in Fig. 14, indicate a minimum mass of 135.8 kg of U^{235} associated with 1-in.-thick layers of plastic separating 4-in.-thick layers of fuel. The maximum mass of 153.1 kg was observed with 1/4-in.-thick layers of plastic and 2-in.-thick fuel layers. Extrapolation to zero thickness gives the critical mass of a homogeneous system as 157.5 kg of U^{235}. Further information concerning the characteristics of these systems was obtained from the flux traverses described in Appendix C, page 55.

Data from all of the experiments with unreflected critical assemblies of the 37.5% U^{235}-enriched UF_4-CF_2 blocks are summarized in Table B-4 and plotted in Fig. 13. Included in these data is the result of a single experiment in which 2-7/8-in.-thick layers of AGHT graphite were used as the moderating material equivalent to total $C:U^{235}$ ratio of 42.2 (the $C:U^{235}$ atomic ratio of the UF_4-CF_2 blocks alone was 2.67). The critical mass of this assembly was 426.7 kg of U^{235}.

Water-Reflected Systems - A number of critical assemblies of the UF_4-CF_2 blocks, reflected on sides and bottom by water, and on the top by a 6-in.-thick slab of paraffin, were also constructed. These assemblies had $H:U^{235}$ ratios from 0.1 to 10.7, achieved by interleaving plastic as before. Data from these assemblies are shown in Table B-6 and Fig. 15 in which the variation of critical mass with $H:U^{235}$ ratio at the 37.5% enrichment is compared to earlier data[5] at 29.8% enrichment.

As noted above, a 1/16-in.-thick rubber sack was used to protect the blocks from water, and a pair of experiments were specifically performed to evaluate the effect of the rubber. In the first of these the customary 1/16-in.-thick sack was used, while the second employed a 1/8-in.-thick sack. From the results of this comparison it is estimated that the use

5. C. K. Beck, A. D. Callihan, and R. L. Murray, Critical Mass Studies, Part II, K-126, Jan. 23, 1948.

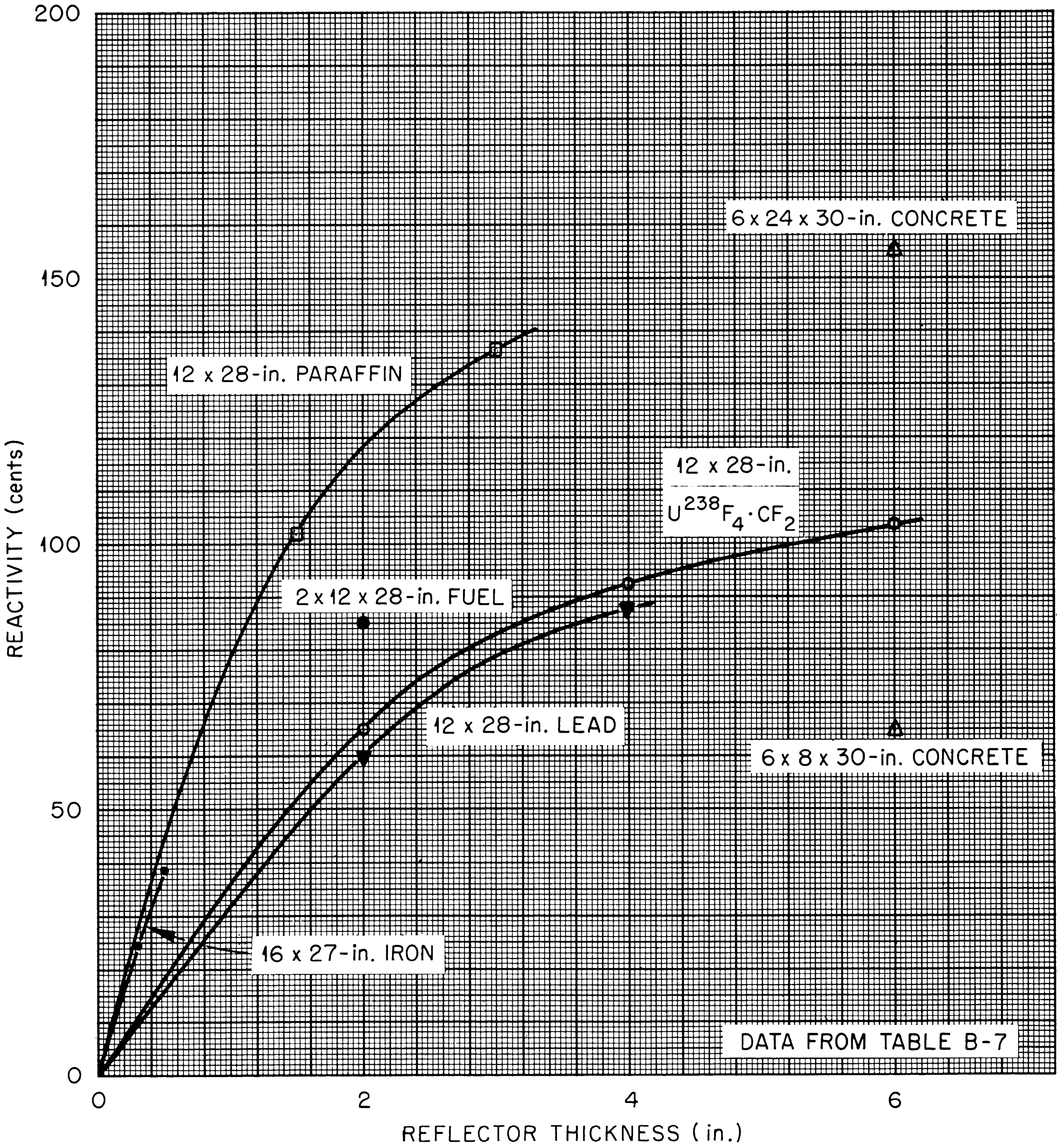

Fig. 12. Reactivity as a Function of the Thickness of Various Reflecting Materials Placed Against One Face of an Otherwise Unreflected Assembly of 37.5 wt % U^{235}-Enriched $UF_4 \cdot CF_2$.

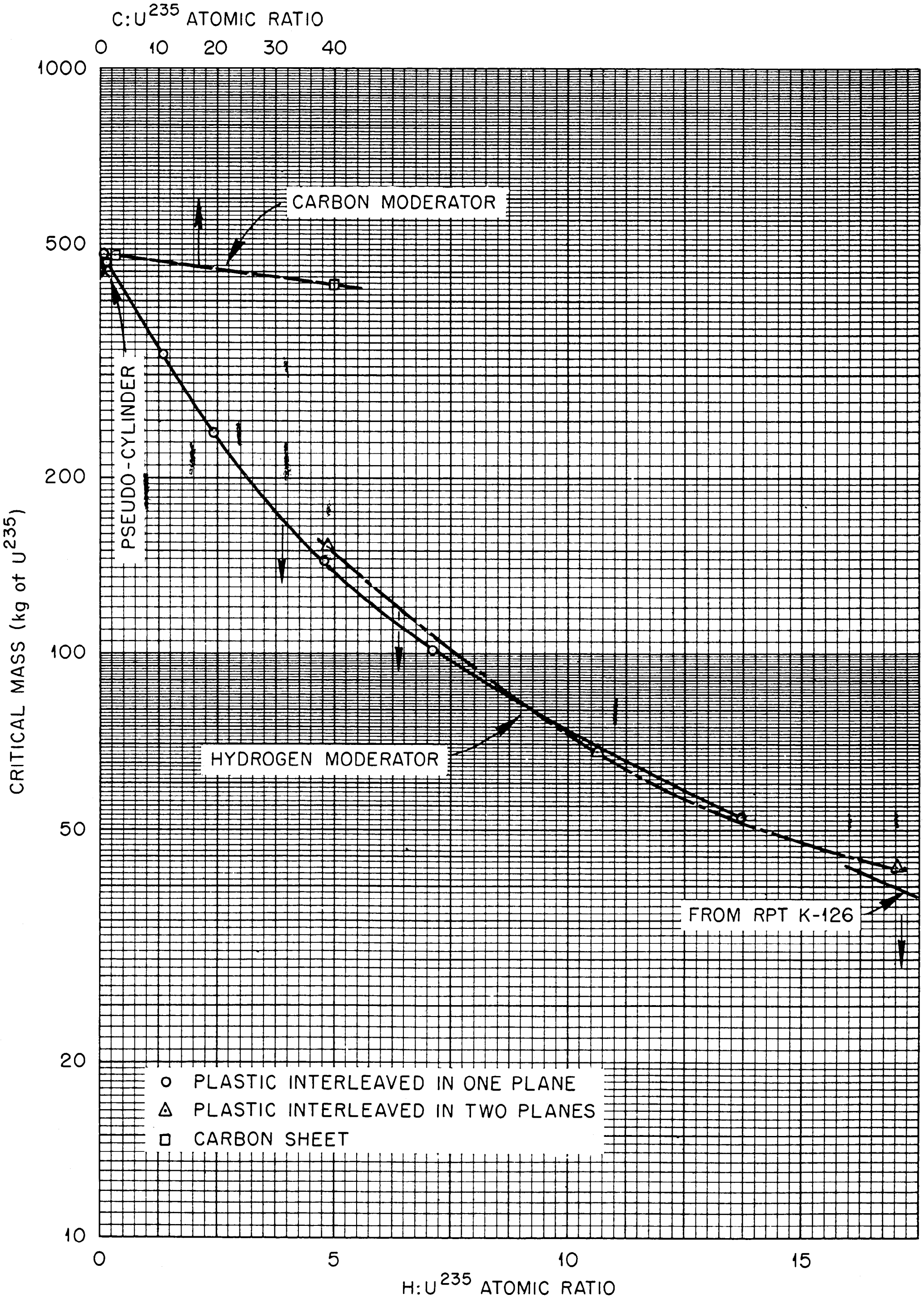

Fig. 13. Critical Mass of Unreflected Cubical $UF_4 \cdot CF_2$ (37.5 wt % U^{235}-Enriched Uranium) Assemblies as a Function of H:U^{235} Atomic Ratio, for Several Moderator Configurations.

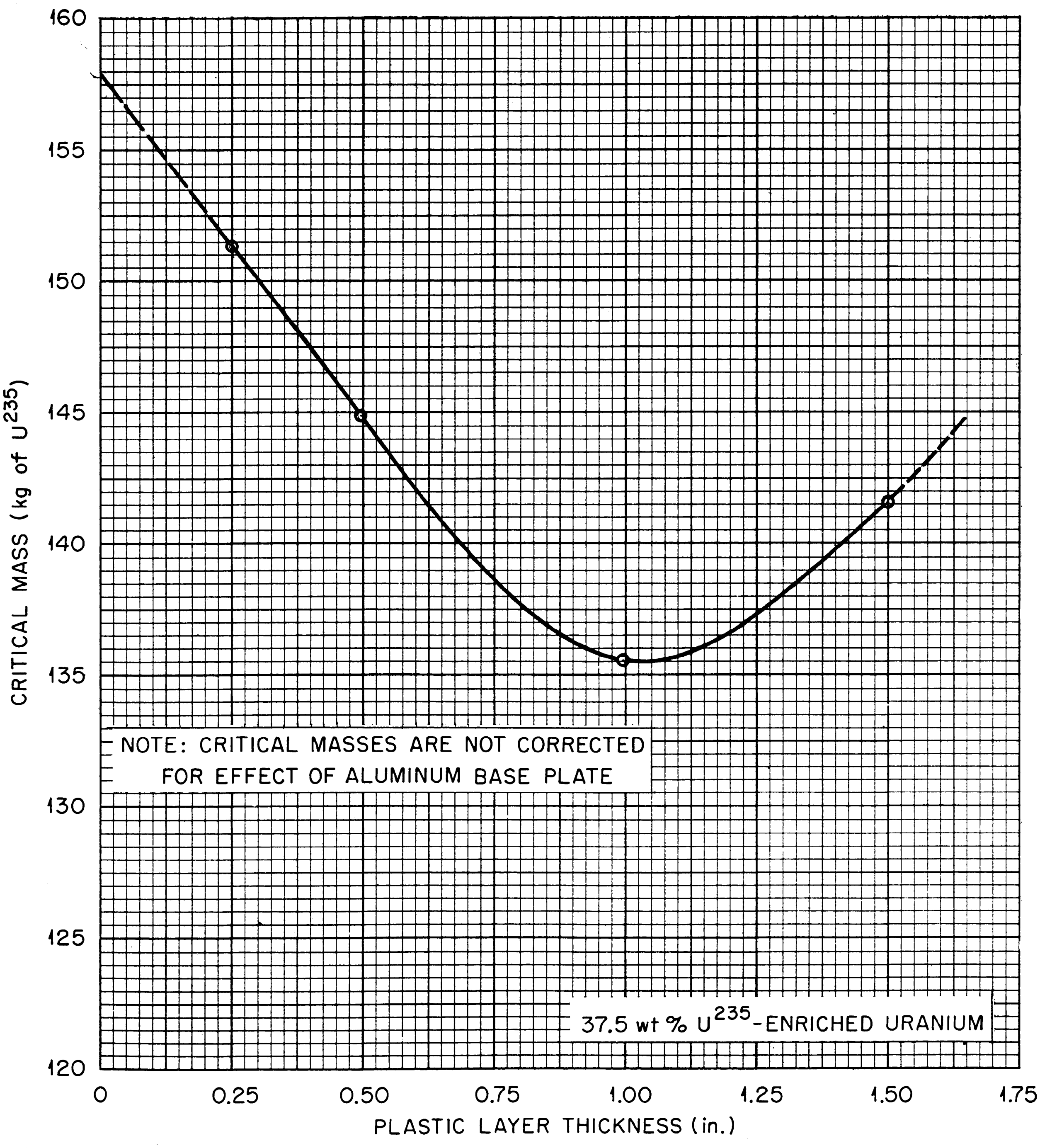

Fig. 14. Critical Mass of an Unreflected UF_4-CF_2 Assembly as a Function of the Thickness of the Plastic Moderator Sheet. $H:U^{235}$ Atomic Ratio = 4.82.

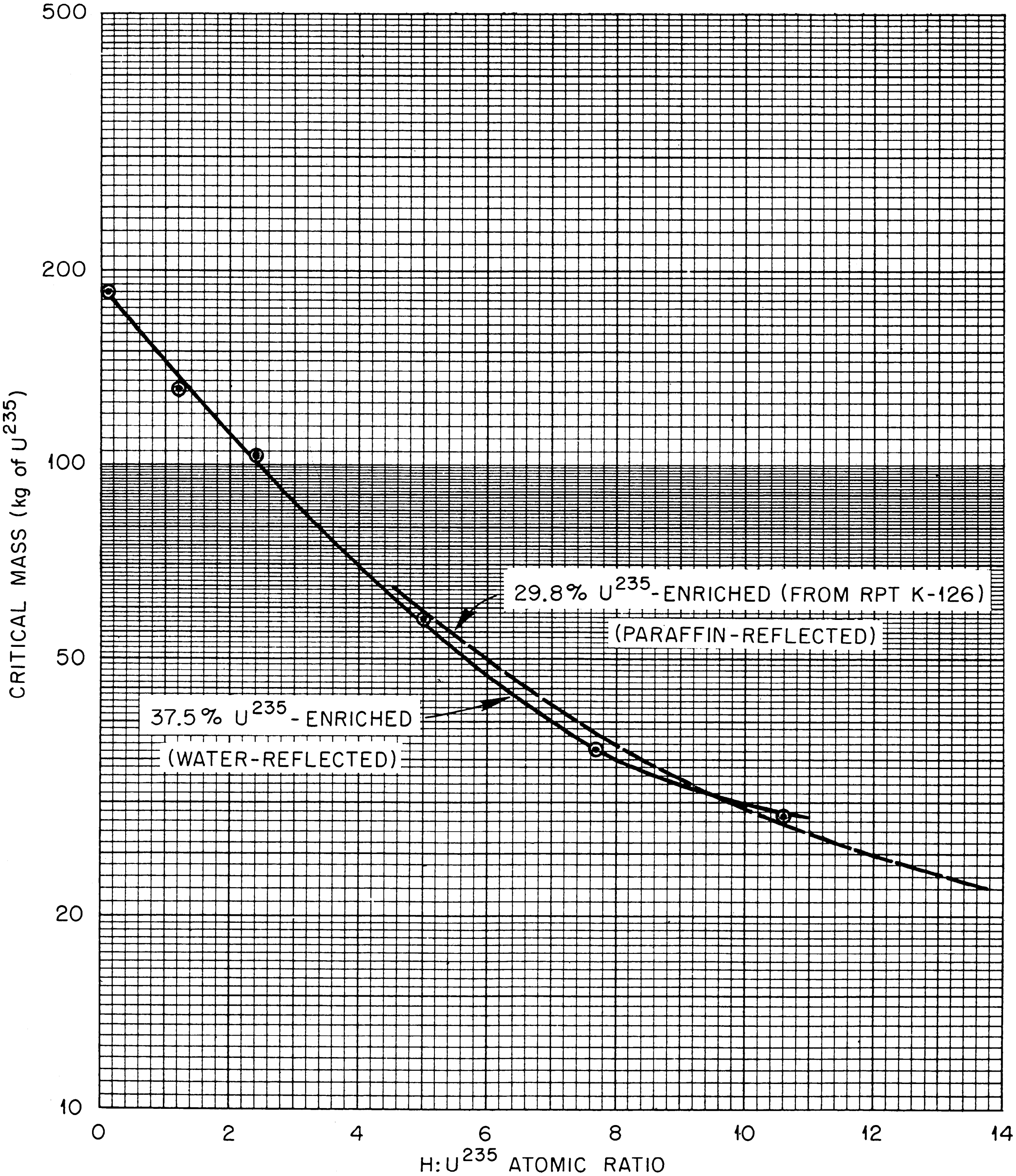

Fig. 15. Critical Mass of a Reflected $UF_4 \cdot CF_2$ Assembly as a Function of $H:U^{235}$ Atomic Ratio for Two Enrichments.

of the 1/16-in.-thick rubber increased the critical mass $\sim 2\%$.

UF_4-CF_2 Mixtures with Average Enrichments of 12.5, 18.8, 25, and 30% U^{235}

Unreflected Systems - Latticing of blocks of UF_4-CF_2 (99.8 wt% U^{238}) and the blocks containing 37.5% U^{235} enriched UF_4, in ratios of 4:1, 2:1, 1:1, and 1:2 produced assemblies simulating, respectively, 12.5, 18.8, 25, and 30% enrichments. Critical parameters derived from these measurements are given in Table B-7, and the critical masses are plotted as a function of $H:U^{235}$ ratio in Fig. 16. Also from the data shown in Table B-7 the variation of critical mass with enrichment can be interpolated for a constant moderation and this has been plotted for $H:U^{235}$ atomic ratios of 7 to 14 in Fig. 17. For these moderations the critical mass is a monotonically decreasing function of enrichment. The addition of hydrogen moderator in the form of plastic sheets was necessary to achieve criticality at all of these enrichments. It must be emphasized that these data are valid only for the grossly heterogeneous systems studied, and are not necessarily applicable to assemblies of greater or lesser homogeneity.

Water-Reflected Systems - Simulated enrichments of 12.5 and 18.8 wt% U^{235} were assembled in a 1/16-in.-thick wall rubber sack as previously described. Data from these assemblies are shown in Table B-6 and Fig. 18. During this series of experiments an estimate was made of the effect on critical conditions of the heterogeneity introduced in these assemblies by the finite sized blocks containing uranium differing in U^{235} enrichment. Keeping the overall average enrichment and the assembly base dimension (36 x 36 in.) constant, the dimensions of unit cells within an assembly were increased from 2 x 2 x 3 in., in which blocks of different enrichment were alternated, first to 2 x 4 x 3 in.where two like blocks were adjacent in one dimension, and then to 4 x 4 x 3 in., two like blocks adjacent in two dimensions. The resulting critical masses were, respectively, 443.6, 452.0 and 460.4 kg of U^{235}. Extrapolation of these values to "zero" heterogeneity yielded 433 kg of U^{235} as the mass in a reflected critical parallelepiped 36 x 36 x 34.5 in. high.

V - CONCLUSIONS

The effects of inhomogeneity and latticing indicated in the simulated 12.5, 18.8, and 30 wt% U^{235}-enriched systems by the foil traverses reported in Appendix C, page 59, preclude an extrapolation of the experimental data to minimum values of the critical mass and the critical volume. For the 4.89 and 37.5 wt% U^{235}-enriched systems, however, at least where the fuel was homogeneous, the experimental data have been analyzed by methods of elementary diffusion theory. For the 4.89% U^{235}-enriched material, the extrapolation distance at each concentration was determined by equating the geometric bucklings for several critical geometries. Table B-8, page 51, gives these empirically derived values of the extrapolation distance and the calculated bucklings for the U_3O_8-Sterotex mixtures, while similar information for the

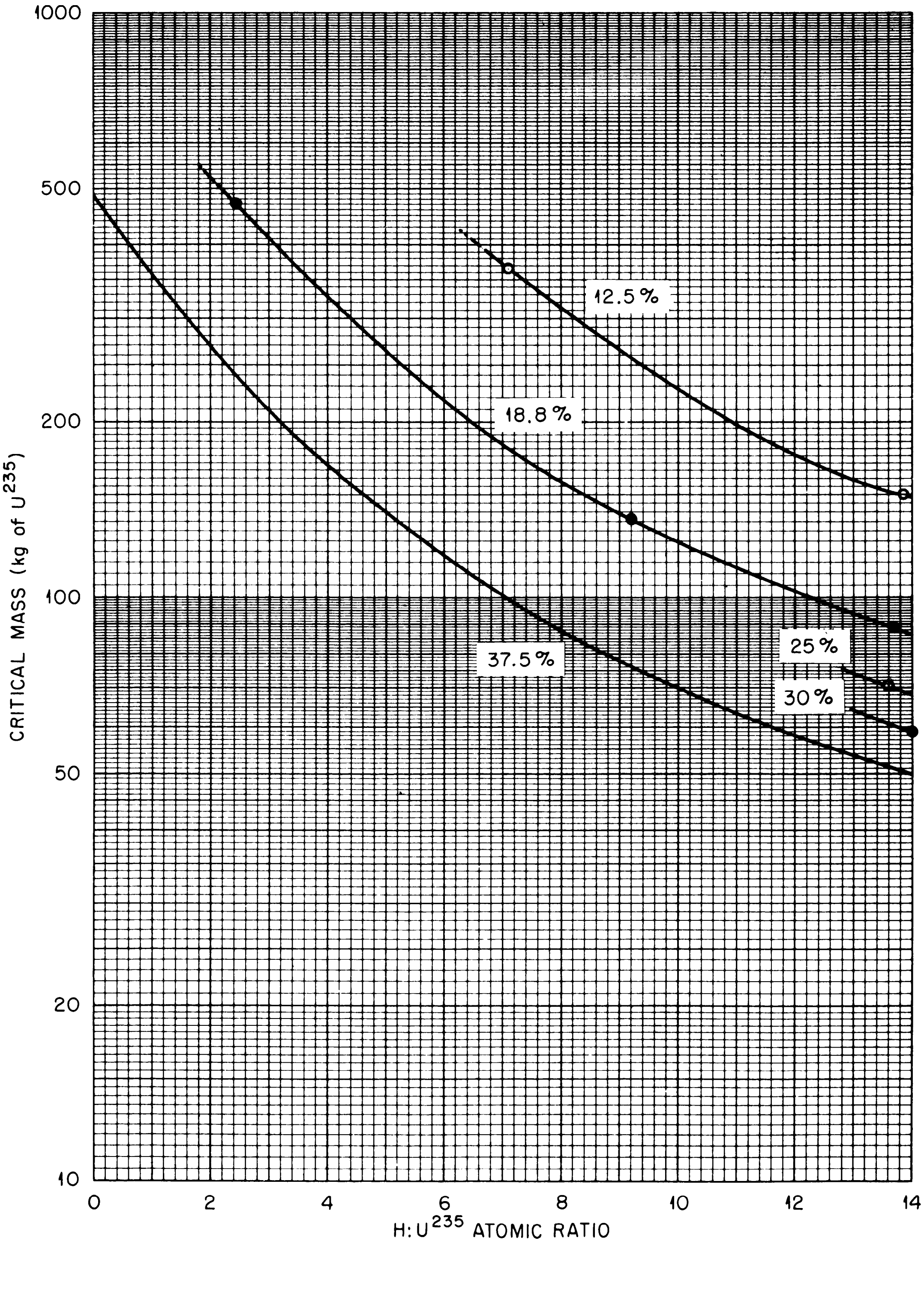

Fig. 16. Critical Mass of an Unreflected UF_4–CF_2 Assembly as a Function of the H:U^{235} Atomic Ratio, for Various Simulated U^{235} Enrichments.

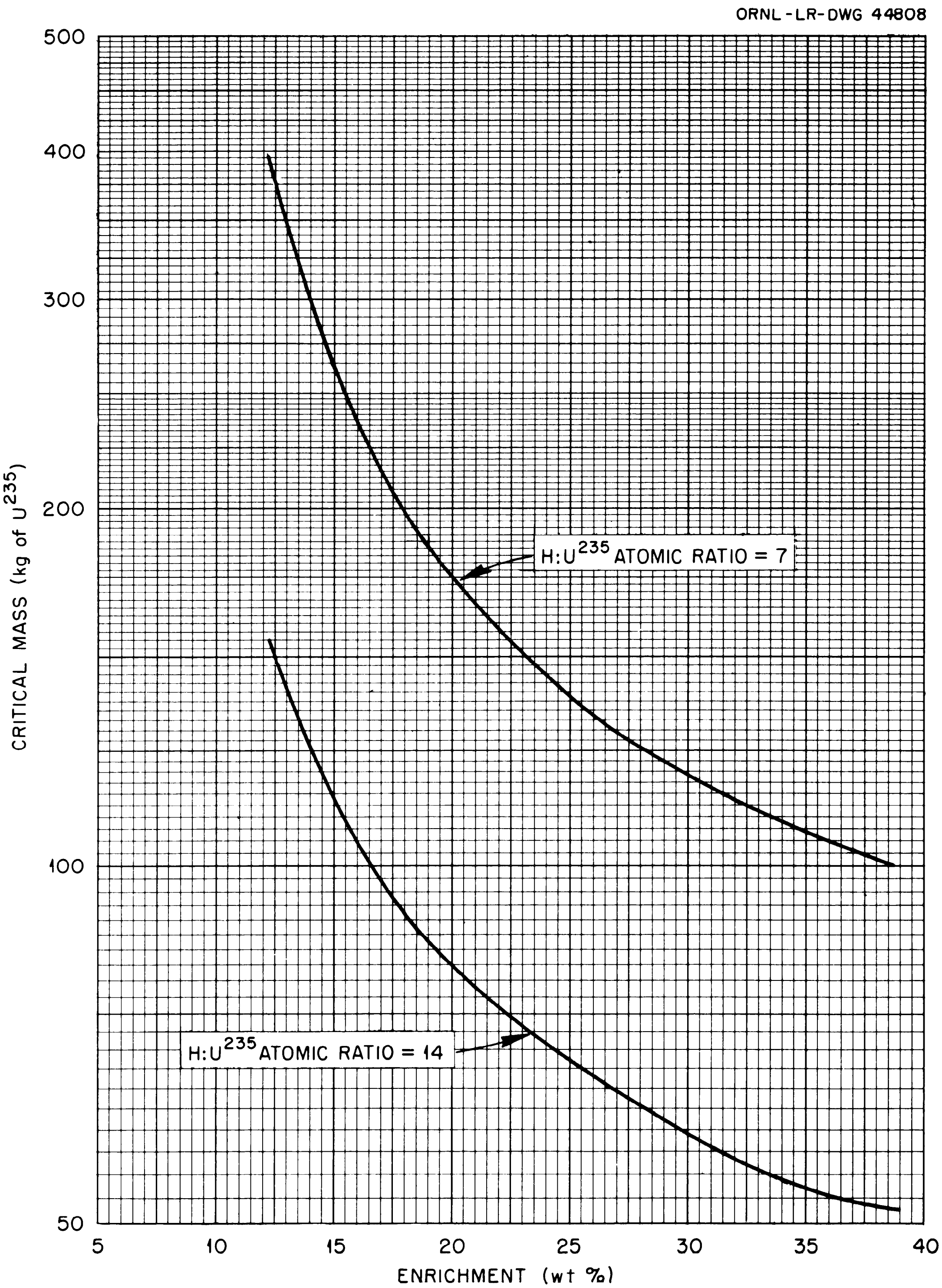

Fig. 17. Critical Mass of Unreflected UF_4-CF_2 Assemblies as a Function of Enrichment, for Two Moderator Ratios.

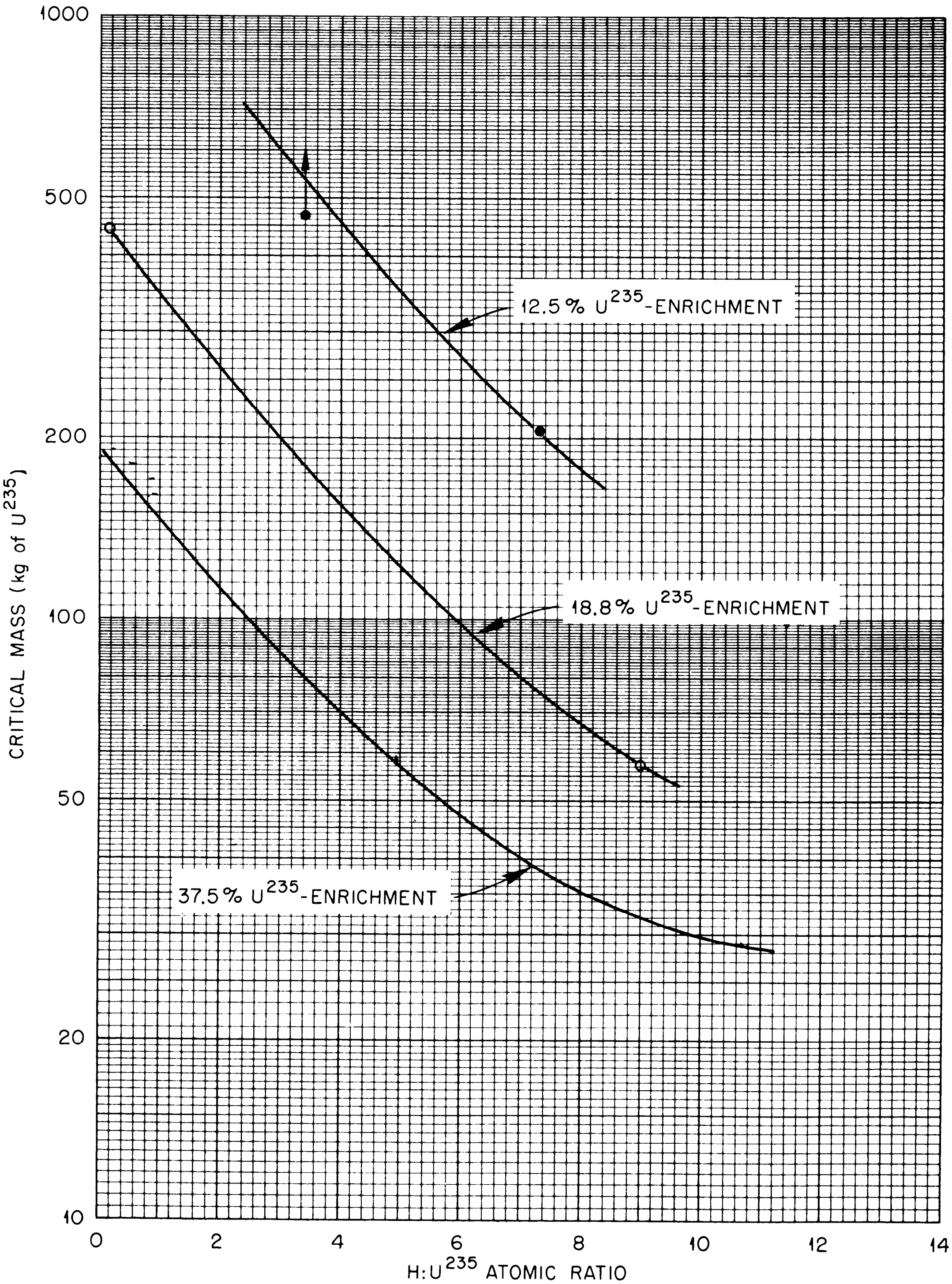

Fig. 18. Critical Mass of a Water-Reflected UF_4-CF_2 Assembly as a Function of $H:U^{235}$ Atomic Ratio for Various Simulated Enrichments.

UO_2F_2 solutions is presented in Table B-9. In Fig. 19 buckling is plotted as a function of $H:U^{235}$ atomic ratio for both U_3O_8-Sterotex mixtures and UO_2F_2 solutions.

With satisfactory values of buckling and extrapolation distance determined, it was possible to establish the dimensions of infinite critical cylinders and slabs, and these results are given for the U_3O_8-Sterotex mixtures in Table B-10, and for the UO_2F_2 solutions in Table B-11.

Table B-12 gives the critical dimensions of U_3O_8-Sterotex mixtures in regular geometries for various $H:U^{235}$ atomic ratios, and Table B-13 shows equivalent data for UO_2F_2 solutions.

Figure 20 plots the critical mass of spheres of both U_3O_8-Sterotex and UO_2F_2 solution as a function of moderation, and Figs. 21 and 22 show the calculated radii of critical spheres of these materials as a function of $H:U^{235}$ atomic ratio.

Figures 23 and 24 show the critical diameters of infinitely long cylinders and critical thicknesses of infinite slabs of UO_2F_2 solution as a function of $H:U^{235}$ atomic ratio for both unreflected and water-reflected aluminum and stainless steel containers.

The critical diameters of infinitely long cylinders and the critical thicknesses of infinite slabs of the U_3O_8-Sterotex mixtures as a function of $H:U^{235}$ atomic ratio is given for the unreflected case in Fig. 25, and for the case of an infinite water reflector in Fig. 26.

From an examination of the foregoing data a number of minimum critical volumes and masses have been determined and are shown in the following table.

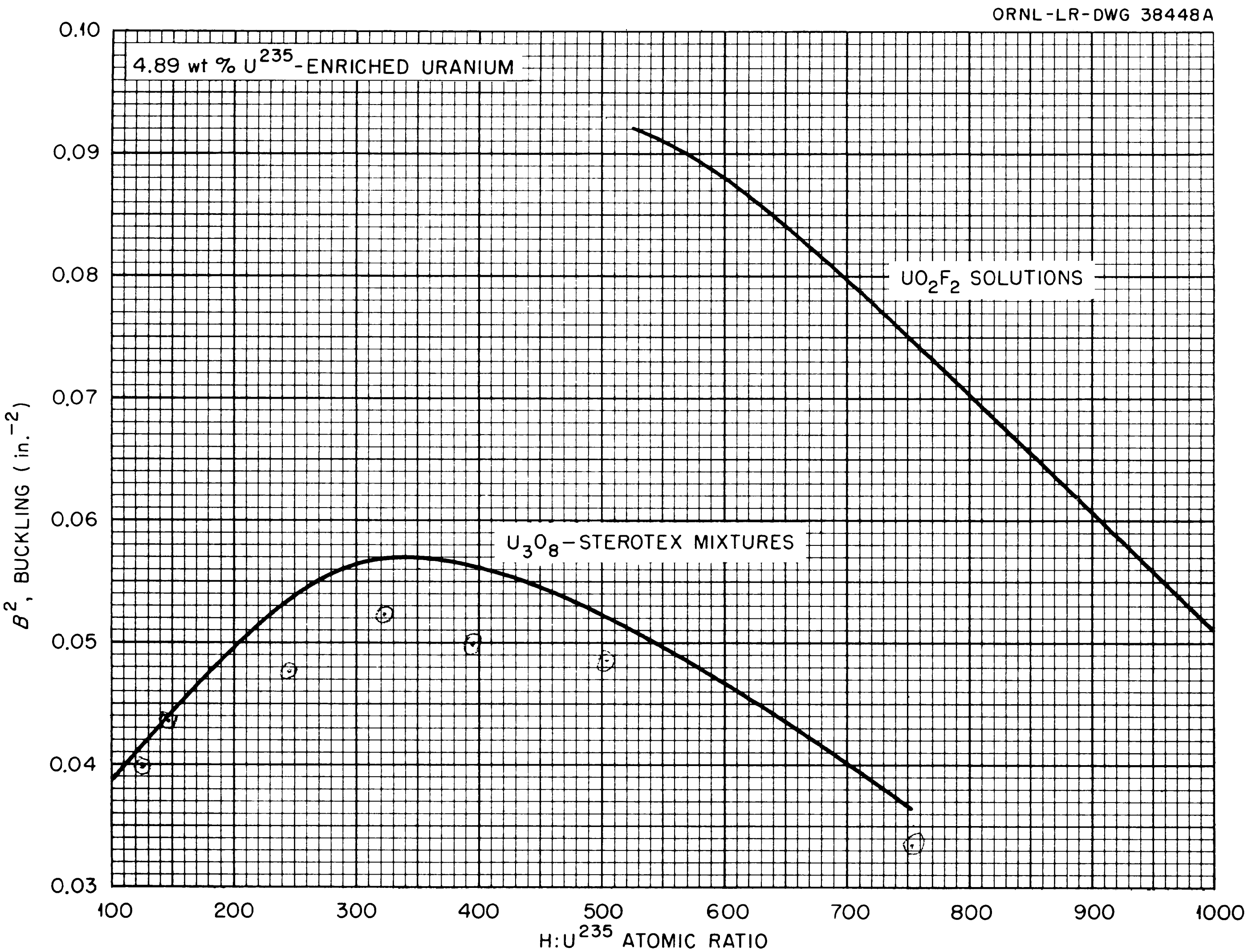

Fig. 19. Estimated Buckling for U_3O_8–Sterotex Mixtures and UO_2F_2 Solutions as a Function of the $H:U^{235}$ Atomic Ratio.

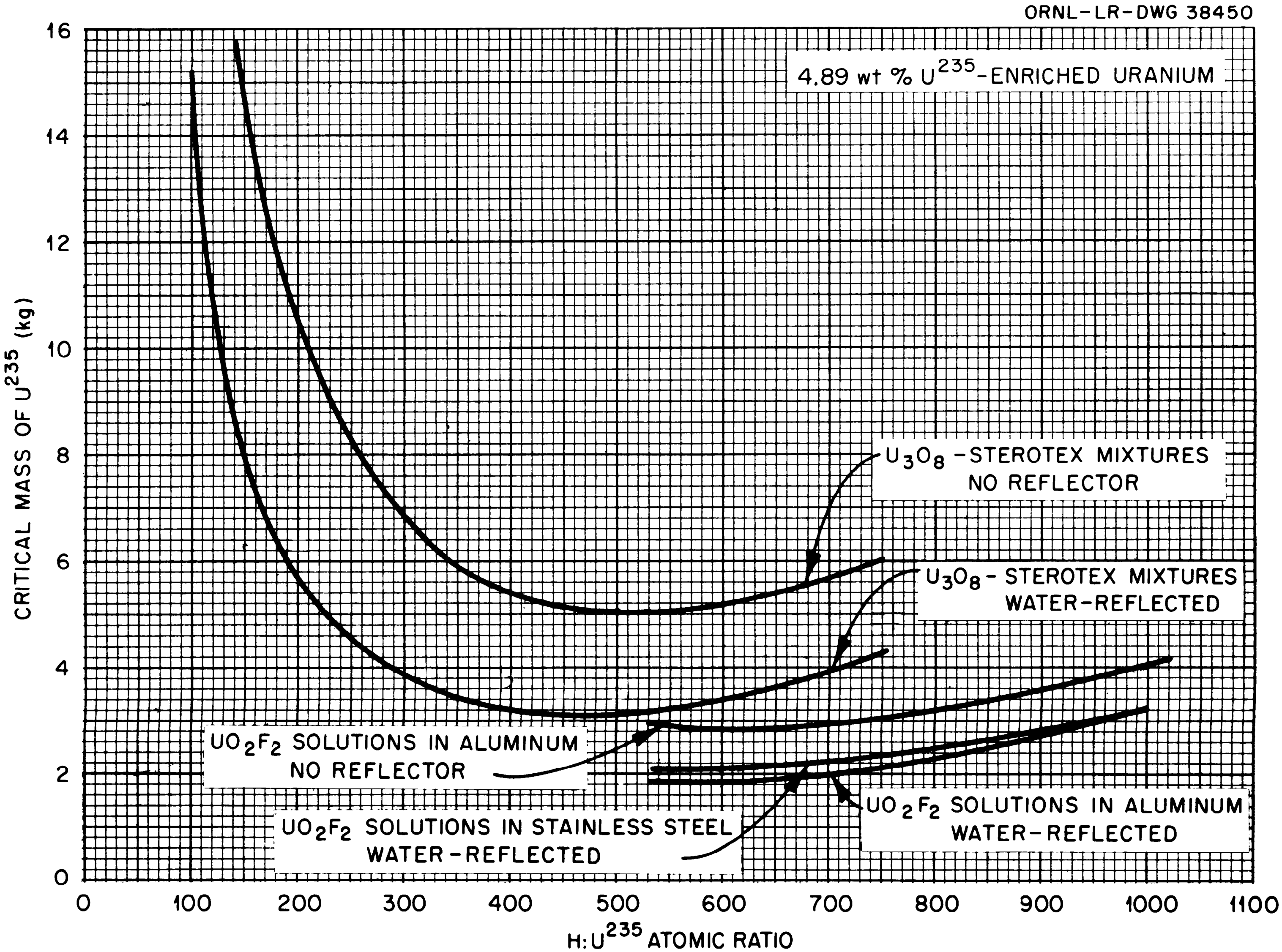

Fig. 20. Estimated Critical Mass of Spheres of UO_2F_2 Solutions and U_3O_8 – Sterotex Mixtures as a Function of H:U^{235} Atomic Ratio.

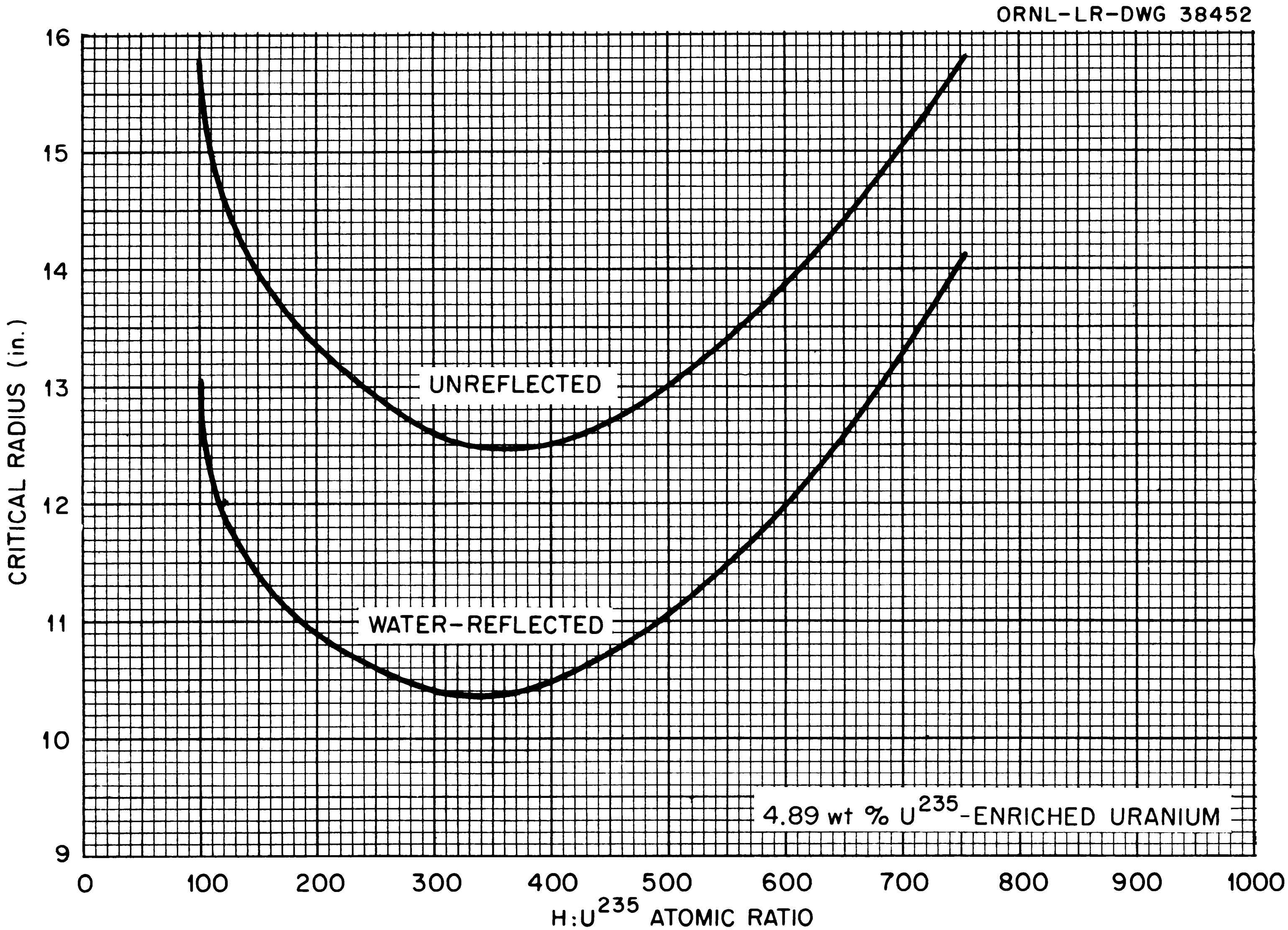

Fig. 21. Calculated Critical Radii of Spheres of U_3O_8–Sterotex Mixtures as a Function of $H:U^{235}$ Atomic Ratio.

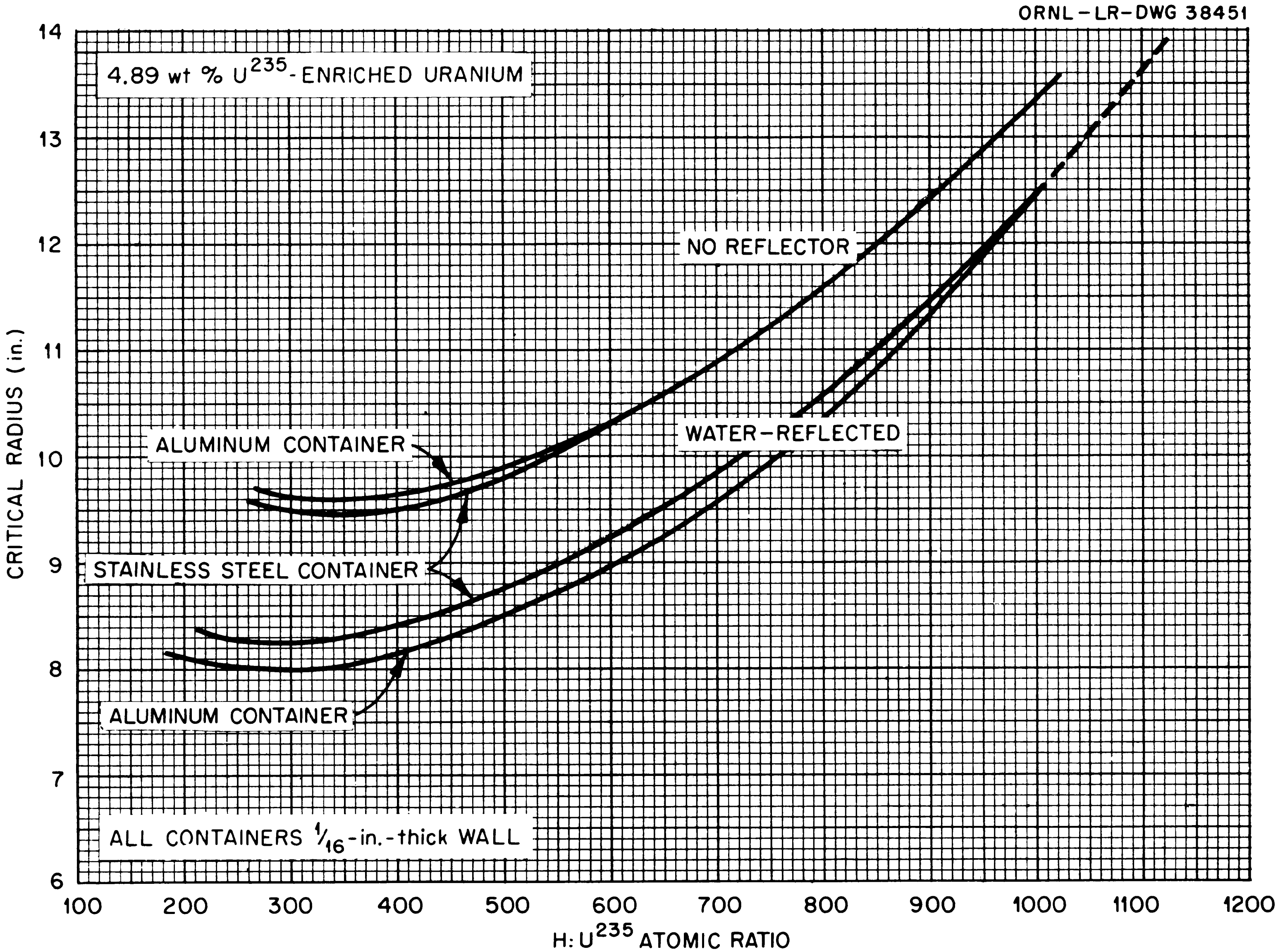

Fig. 22. Calculated Critical Radii of Spheres of UO_2F_2 Solution as a Function of H:U^{235} Atomic Ratio.

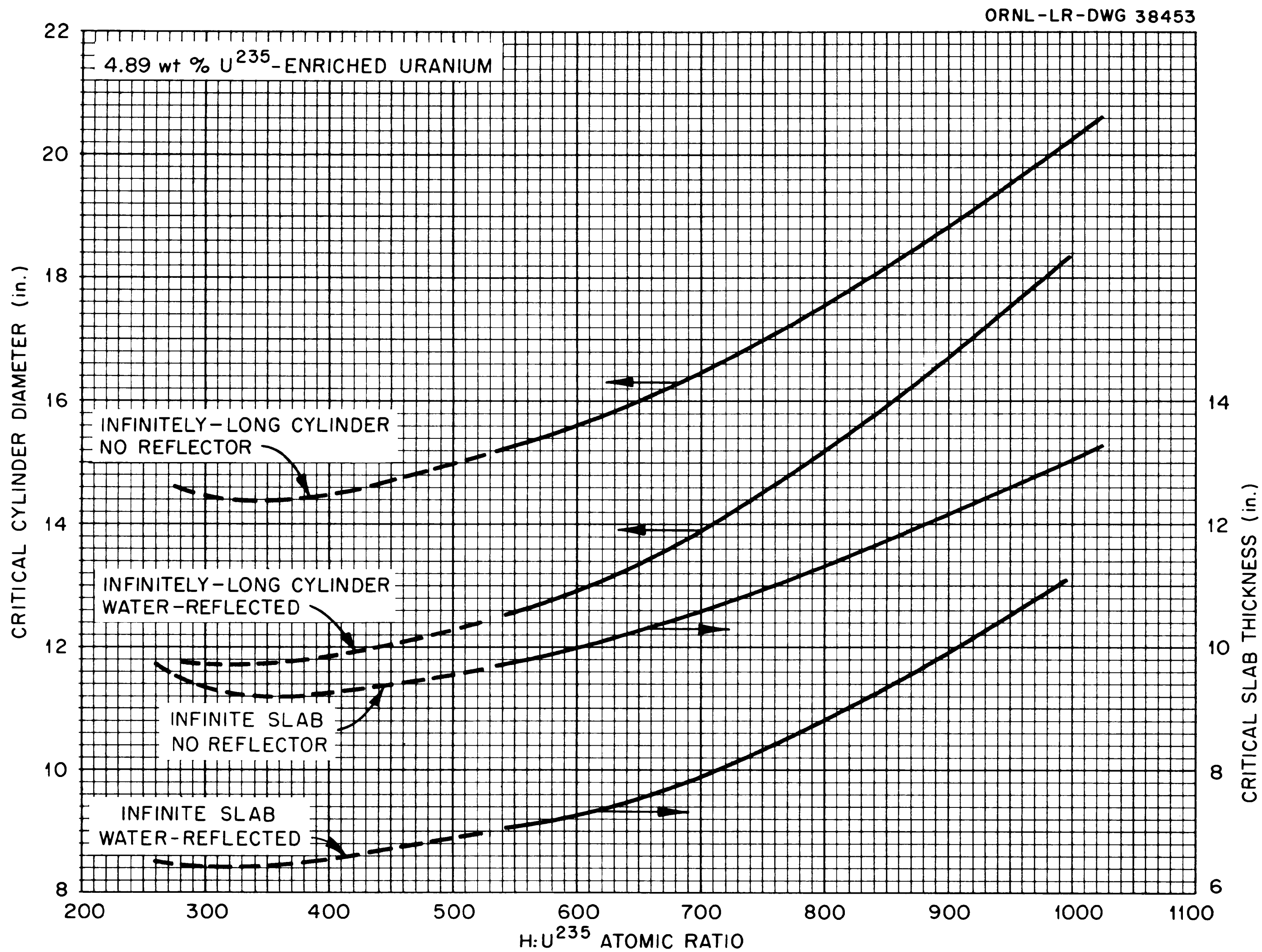

Fig. 23. Critical Diameters of Infinitely Long Cylinders and Critical Thicknesses of Infinite Slabs of UO_2F_2 Solution as a Function of $H:U^{235}$ Atomic Ratio (Aluminum-Walled Reactor).

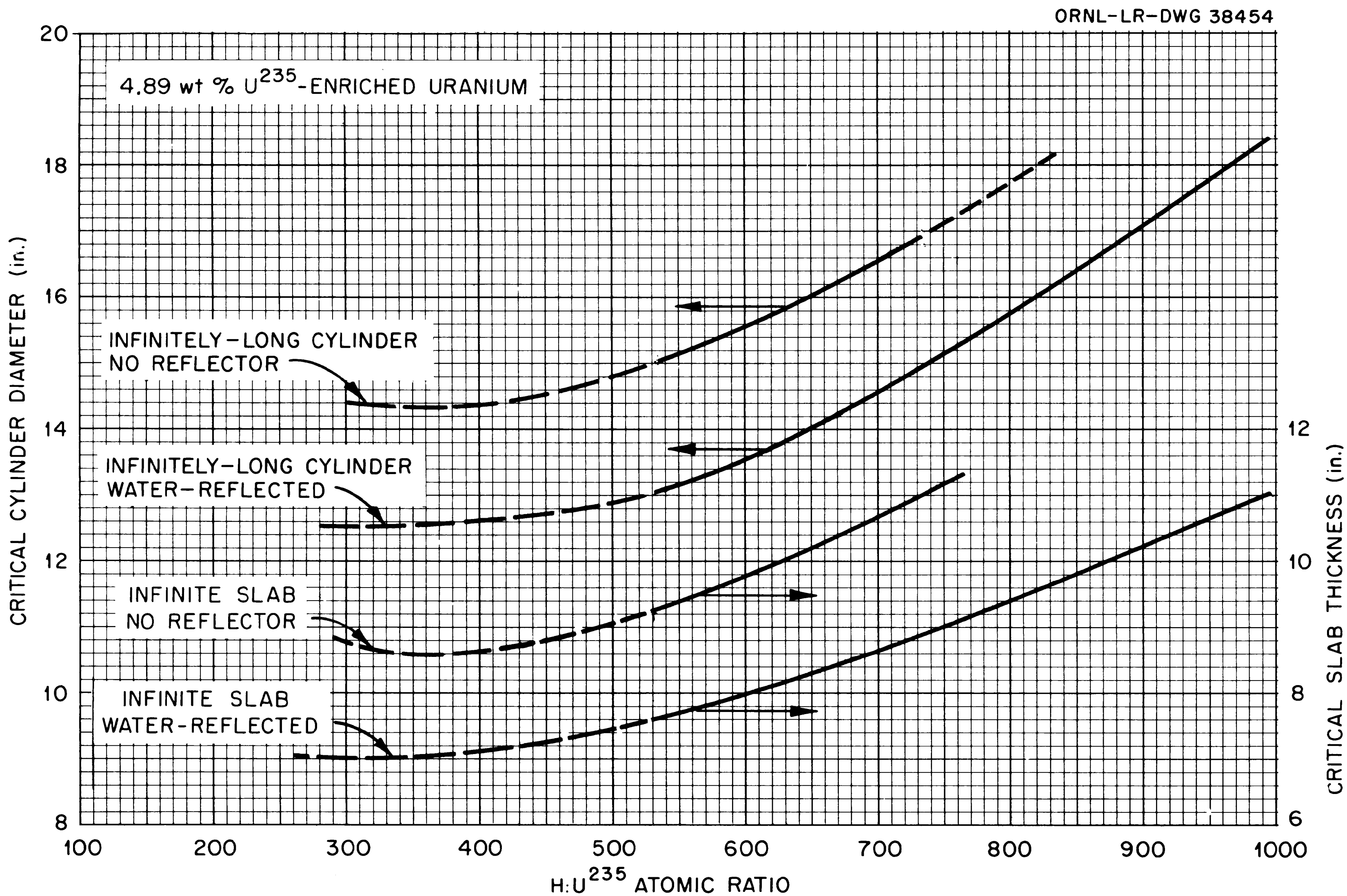

Fig. 24. Critical Diameters of Infinitely-Long Cylinders and Critical Thicknesses of Infinite Slabs of UO_2F_2 Solution as a Function of $H:U^{235}$ Atomic Ratio (Stainless-Steel-Walled Reactor).

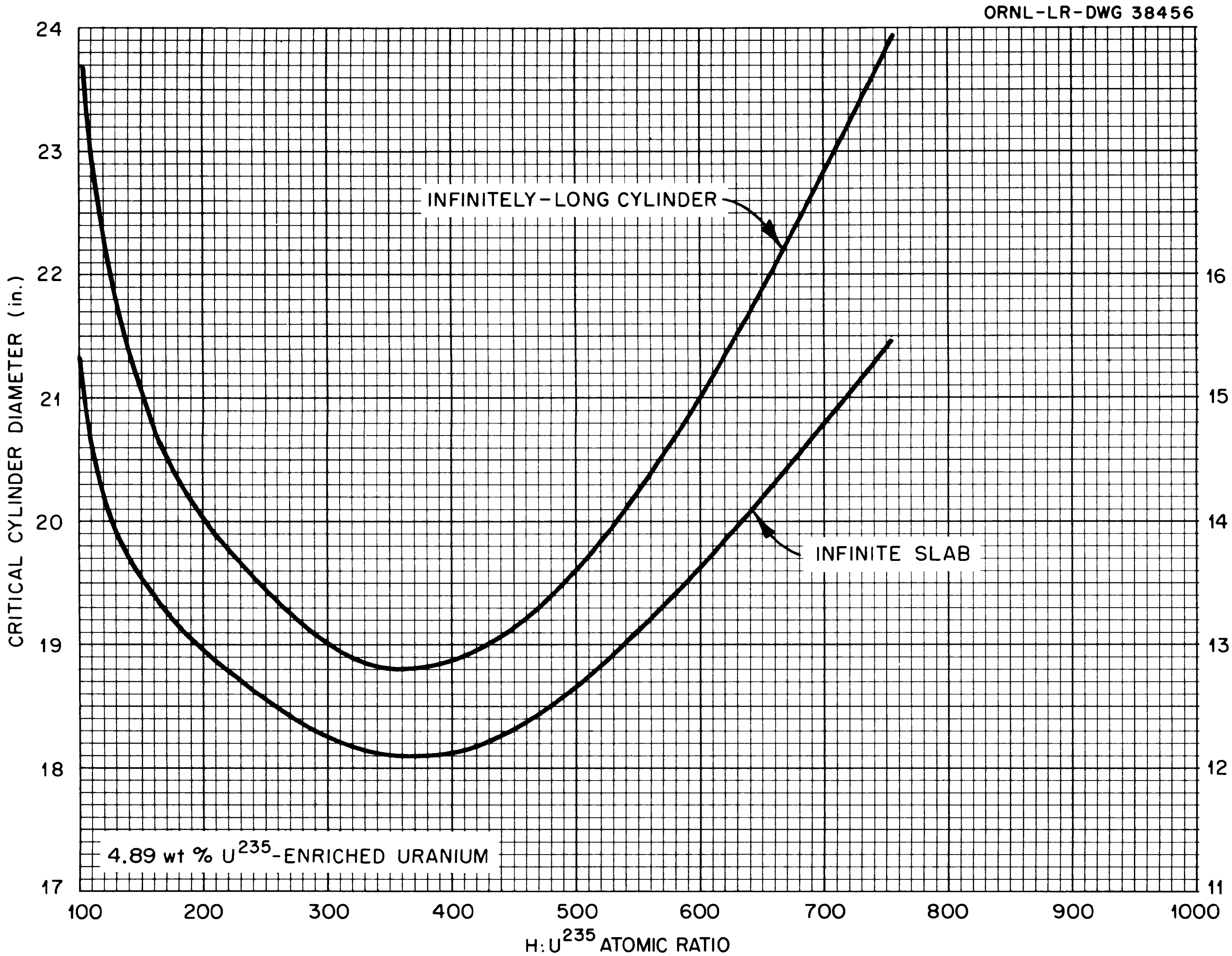

Fig. 25. Critical Diameters of Infinitely-Long Cylinders and Critical Thicknesses of Infinite Slabs of Unreflected U_3O_8 – Sterotex Mixtures as a Function of $H:U^{235}$ Atomic Ratio.

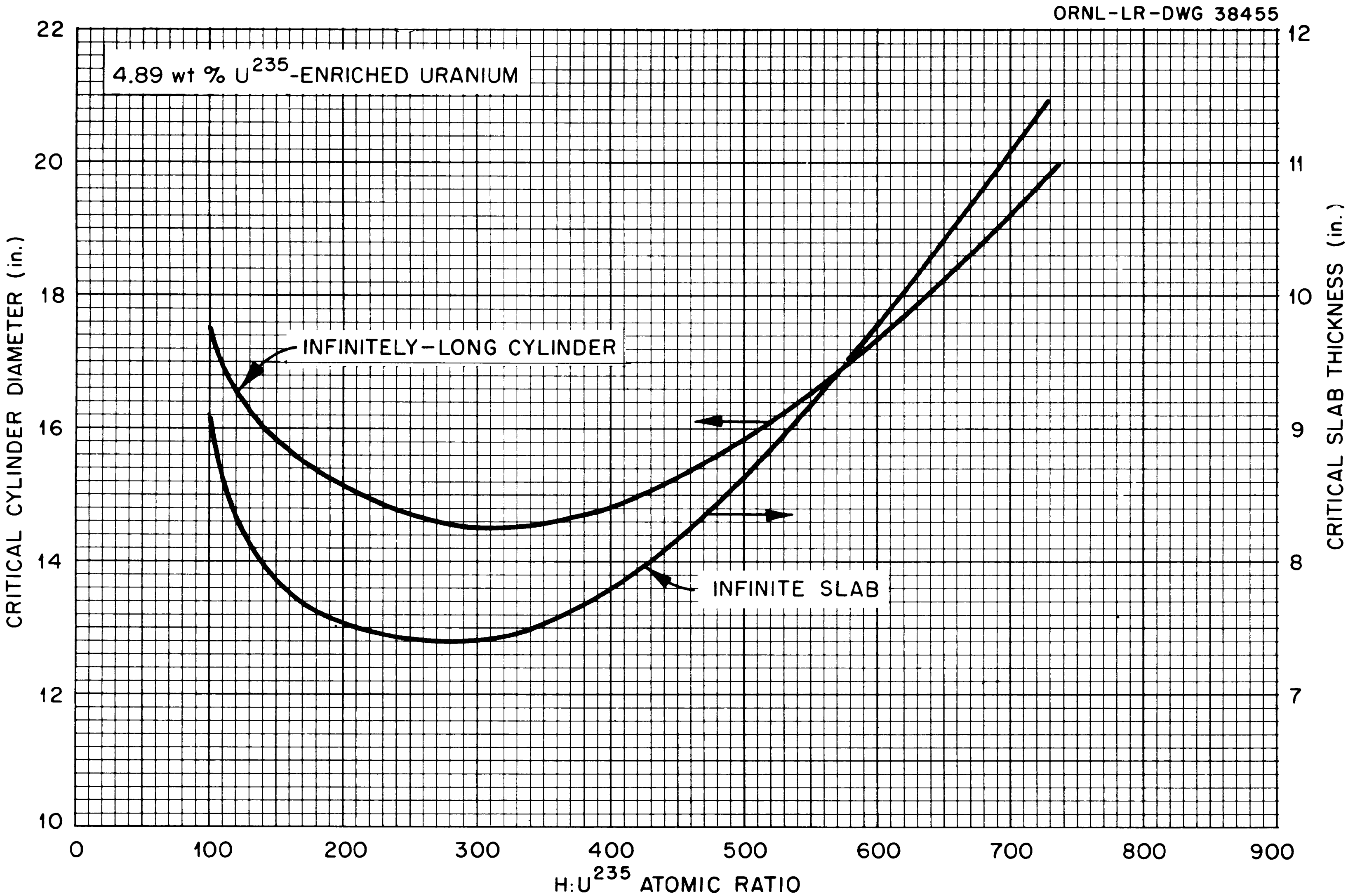

Fig. 26. Critical Diameters of Infinitely-Long Cylinders and Critical Thicknesses of Infinite Slabs of U_3O_8 – Sterotex Mixtures With Infinite Water Reflector as a Function of $H:U^{235}$ Atomic Ratio.

Estimated Minimum Critical Parameters of 4.89 wt% U^{235}
Enriched Uranium in Spherical Geometry

	$H:U^{235}$ Ratios	Mass (kg)	Volume (liters)
		U_3O_8-Sterotex Systems	
Water-Reflected	340	-	76.1
	450	3.05	-
Unreflected	370	-	132.5
	500	5.0	-
	UO_2F_2 Solutions - 1/16-in.-wall Aluminum Containers		
Water-Reflected	300	-	35.2
	450	1.9	-
Unreflected	350		60.7
	600	2.4	-
	UO_2F_2 Solutions - 1/16-in.-wall Stainless Steel Containers		
Water-Reflected	300	-	38.5
	450	2.05	-

For the analysis of the 37.5% U^{235}-enriched UF_4-CF_2 systems, an extrapolation length of 0.80 in. was assigned by averaging values obtained from flux measurements in an unmoderated assembly. The minimum critical volume estimated for this material is that of a 16.6-in.-radius sphere. No attempt has been made to interpret the results from measurements on other UF_4-CF_2 systems. Gross inhomogeneities occasioned by the latticing of moderator or fuel and diluent precluded further analysis.

VI - ACCURACY

Although the uranium content of the experimental materials was determined by chemical analysis to a stated accuracy of ± 0.1%, nonuniformities in the mixtures of solids (U_3O_8-Sterotex and UF_4-CF_2) and sampling errors in the large volumes of solutions decreased the estimated accuracy of the uranium content to ± 0.5%.

The critical masses of the solids (4.89%-enriched U_3O_8 and 37.5%-enriched UF_4) were obtained from the weight of the material assembled and the uranium analysis and are known to ± 0.5%. The dimensions, and hence the volume, were determined by direct measurement and the accuracy depended upon how well the units fitted together. Irregularities in both the structure of the aluminum boxes containing the U_3O_8 and in their stacking caused an uncertainty of ± 2% in the linear dimensions. Since the blocks of 37.5% UF_4-CF_2 were more true in their individual dimensions, an accuracy of ± 1% is assigned to the dimensions of these assemblies.

The solutions were made critical principally in cylindrical vessels whose capacities, as a function of liquid height, were predetermined. From the observed critical height, the critical volume and mass were obtained with accuracies of ± 0.1% and of ± 0.5%, respectively. The diameters of the cylinders were known to ± 0.5%.

The uncertainties in critical parameters estimated from the extrapolation of source neutron multiplication curves are appended to the values tabulated in the data.

Appendix A

EXPERIMENTAL MATERIALS

Table A.1 - Composition of Uranium Materials

Isotopic Analysis, wt%	U_3O_8	UO_2F_2	UF_4-CF_2	UF_4-CF_2
U^{234}	0.02	0.02	0.2	-
U^{235}	4.89	4.89	37.5	0.2
U^{236}	-	-	0.2	-
U^{238}	95.09	95.09	62.1	99.8
Chemical Analysis, wt%				
Uranium	84.47	77.16	65.50	65.52
Fluorine	-	12.45	31.2	31.2
Hydrogen (as water)	0.008	-	0.01	0.01
Carbon	-	-	3.3	3.3
Oxygen	15.52	10.38	-	-

Table A.2 - Spectrographic Analysis of UO_2F_2 Solution

Element	ppm	Element	ppm
Aluminum	25	Lithium	< 0.2
Antimony	< 4	Magnesium	2
Arsenic	< 20	Manganese	1
Barium	< 4	Mercury	< 4
Beryllium	< 0.02	Molybdenum	800
Bismuth	< 1	Nickel	3
Boron	0.1	Palladium	< 1
Cadmium	0.8	Phosphorus	< 100
Calcium	< 10	Potassium	< 100
Chromium	2	Silicon	50
Cobalt	< 1	Silver	350
Copper	7	Sodium	12
Gallium	< 1	Strontium	< 10
Germanium	< 0.4	Thallium	< 2
Gold	< 2	Tin	2
Indium	< 4	Titanium	a
Iron	35	Vanadium	< 0.5
Lead	15	Zinc	< 10

a. Ground in TiC crucible.

Table A-3 - Analysis of Sterotex (Glycerol Tristearate)

Chemical formula	$(C_{17}H_{35}CO_2)_3C_3H_5$
Molecular weight	891.5
Density, g/cc	0.862
Hydrogen density, g/cc	0.1072[a]

Material	wt%	Material	wt%
Carbon	76.5	H_2O	0.23
Hydrogen	12.8	Oxygen	10.8 (Calc.)
Nitrogen	0.06	Ash	0.1

a. This is to be compared with the density of hydrogen in water, 0.1117 g/cc.

Table A-4 - Spectrographic Analysis of Ash in Sterotex

Element	wt% (of ash)	Element	wt% (of ash)
Aluminum	0.08	Manganese	$\leq$ 0.04
Barium	0.04	Molybdenum	$\leq$ 0.04
Beryllium	0.003	Nickel	0.08
Boron	0.008	Platinum	0.3
Cadmium	$\leq$ 0.04	Silicon	0.6
Calcium	0.002	Silver	0.04
Chromium	$\leq$ 0.08	Strontium	$\leq$ 0.06
Cobalt	$\leq$ 0.04	Tin	$\leq$ 0.04
Copper	0.02	Titanium	$\leq$ 0.01
Iron	0.2	Vanadium	$\leq$ 0.04
Lead	0.08	Zinc	1.0
Magnesium	0.02	Zirconium	10

Table A.5 - Compositions of U_3O_8-Sterotex Mixtures*

Uranium Concentration		U^{235} Concentration		Hydrogen Concentration
g/liter	H:U Atomic Ratio	g/liter	$H:U^{235}$ Atomic Ratio	g/liter
3262.4	0.023	159.5	0.478	0.32
2474.9	1.56	121	31.84	16.4
2556.8	3.12	125	63.72	33.9
2176.3	4.04	106.4	82.57	37.4
1932.9	4.97	94.5	101.7	40.9
1824.5	6.07	89.2	124.1	47.1
1689.5	7.18	82.6	146.8	51.7
1425.6	8.40	69.7	171.9	50.8
1327.3	9.72	64.9	198.8	54.9
1139.3	11.96	55.7	244.6	58.0
979.7	15.67	47.9	320.5	65.3
824.3	19.34	40.3	395.6	67.8
767.0	21.95	37.5	448.9	71.6
683.2	24.63	33.4	503.8	71.6
453.7	36.99	22.2	756.6	71.4

* Average of the entire batch at the given concentration.

Table A.6 - Compositions of Aqueous UO_2F_2 Solutions

Uranium Concentration			U^{235} Concentration		Hydrogen Concentration	Specific Gravity
wt%	g/liter	H:U Atomic Ratio	g/liter	$H:U^{235}$ Atomic Ratio	g/liter	
43.93	870.3	25.9	42.54	524	95.1	1.981
40.03	728.5	31.8	35.62	643	97.44	1.820
37.48	650.3	36.4	31.79	735	99.25	1.735
31.74	496.7	49.1	24.28	991	102.4	1.565
31.70	495.5	49.2	24.22	994	102.4	1.563
31.54	491.7	49.6	24.04	1002	102.5	1.559
31.12	481.4	50.7	23.54	1025	102.6	1.547
31.11	481.0	50.8	23.52	1026	102.6	1.546
29.83	452.2	54.4	22.11	1099	103.4	1.516

Table A-7 - Composition of UF_4-CF_2 Blocks and Spectrographic Analyses of Component Materials

Average Analysis of Blocks:

UF_4: 86.44 wt%
$(CF_2)_n$: 13.78 wt% (Total C in $(CF_2)_n$: 23.4%; ash: 0.07%)
H_2O: 0.1 wt% (From weight loss upon heating at 110°C)

Spectrographic Analyses of Components

Element	ppm UF_4	ppm $(CF_2)_n$	Element	ppm UF_4	ppm $(CF_2)_n$
Aluminum	3	5	Lead	-	2
Antimony	-	$\leq$ 4	Lithium	0.2	$\leq$ 0.2
Arsenic	-	$\leq$ 20	Magnesium	-	10
Barium	-	$\leq$ 4	Manganese	1	$\leq$ 1
Beryllium	0.1	$\leq$ 0.1	Mercury	2	-
Bismuth	-	$\leq$ 1	Molybdenum	-	$\leq$ 2
Boron	0.2	0.1	Nickel	5	$\leq$ 1
Cadmium	0.2	$\leq$ 0.1	Palladium	-	$\leq$ 1
Calcium	-	50	Phosphorus	-	$\leq$ 100
Chromium	2	4	Silicon	25	12
Cobalt	1	$\leq$ 1	Sodium	30	30
Gadolinium	-	$\leq$ 1	Sulfur	-	$\leq$ 20
Germanium	-	$\leq$ 0.4	Thallium	-	$\leq$ 4
Gold	3	$\leq$ 1	Tin	-	$\leq$ 1
Indium	2	-	Vanadium	1	$\leq$ 1
Iron	10	6	Zinc	-	$\leq$ 10

Table A.8 - Average Physical Properties of UF_4-CF_2 Blocks

Quantity Available	Dimensions: Length (in.)	Width (in.)	Thickness (in.)	Mass (g)	Density (g/cm^3)	Uranium Content (g)
			37.5% U^{235}			
1717	2.000 ± 0.015	2.000 ± 0.015	3.000 ± 0.015	$944 {+31 \atop -14}$	4.78 ± 0.07	616.56
895	2.000 ± 0.015	2.000 ± 0.015	1.000 ± 0.015	$318 {+3 \atop -4}$	4.78 ± 0.07	207.7
54	1.000 ± 0.010	1.000 ± 0.010	1.000 ± 0.010	$79.6 {+0.7 \atop -1.0}$	4.78 ± 0.07	51.97
			0.2% U^{235}[a]			
2389	2.000 ± 0.015	2.000 ± 0.015	3.000 ± 0.015	944 ± 20	4.78 ± 0.07	616.6
4701	2.000 ± 0.015	2.000 ± 0.015	1.000 ± 0.015	318 ± 3	4.78 ± 0.07	207.7

a. These blocks contained 1% carbon flour which was added to distinguish between enrichments.

Appendix B

TABULATION OF CRITICAL DATA

Table B-1. Parameters of Subcritical U_3O_8-Sterotex Assemblies (4.89 wt% U^{235} Enriched Uranium)

U^{235} Concentration		Final Conditions			
$H:U^{235}$ Atomic Ratio	g of U^{235} per liter	Dimensions (in.)	Volume (liters)	U^{235} Mass (kg)	Apparent Source Neutron Multiplication
Water-Reflected Assemblies					
0.498	159.5	16 x 24 x 20[a]	136.4	21.77	ND[b]
31.84	121	20 x 24 x 24[c]	182.4	22.12	1.5 - 1.6
83.5	106.2	16 x 16 x 40	167.8	17.82	1.45
81.6	106.3	16 x 20 x 40	209.8	22.30	4
81.8	106.8	32 x 40 x 12	282	26.5	20
81.8	106	36 x 32 x 12	227	24.1	8
81.8	106	32 x 32 x 12	201	21.3	4
82.7	106	8 x 40 x 42.8	224	23.74	ND
101.9	95.8	16 x 16 x 40	167.8	16.09	ND
101.7	101.7	32 x 40 x 12.2	256	24.04	2
101.7	95.7	44 x 40 x 8	230.8	22.09	2
124.5	89.0	12 x 12 x 48	113.3	10.09	ND
123.9	89	48 x 44 x 8	276.9	24.63	1.2
146.7	83.3	40 x 44 x 8	230.1	19.16	ND
171.7	69.6	12 x 44 x 19.4	167.8	11.68	2.0
172.0	69.5	8 x 44 x 44.6	257.0	17.86	ND
197.8	65.2	12 x 12 x 48	113.3	7.39	ND
198.3	66.7	40 x 44 x 8	230.8	15.39	ND
244.2	55.6	8 x 40 x 44	230.8	12.83	ND
244.2	55.2	12 x 12 x 48	113.3	6.26	1.05
320.5	47.7	8 x 40 x 44	230.8	11.0	ND
320.7	47.1	12 x 12 x 48	113.3	5.33	ND
395.5	40.56	8 x 44 x 44	253.9	10.30	ND
395.5	40.4	12 x 12 x 44	101.4	4.10	ND
756.1	22.2	20 x 20 x 40	262.3	5.81	2.6
758.6	22.9	16 x 16 x 40	167.8	3.84	1.05
Unreflected Assemblies					
198.1	65.71	16 x 16 x 16	67.1	4.41	ND
197.5	64.9	20 x 20 x 20	131.1	8.52	2.3
200.7	64.8	20 x 24 x 23.6	185.7	12.03	3.7

a. Plus an additional 4 x 8 x 16 layer on the 20 x 24 in. face.
b. Not detectable.
c. With a 4 x 4 x 24 in. section missing from one edge.

Table B-2 - Critical Parameters of U_3O_8-Sterotex Assemblies
(4.89 wt% U^{235} Enriched Uranium)

U^{235} Concentration		Critical Conditions		
$H:U^{235}$ Atomic Ratio[a]	g of U^{235} per liter	Dimensions (in.)	Volume (liters)	U^{235} Mass (kg)
		Water-Reflected Assemblies		
63.7	125	(24.7 x 24.7 x 24.7) ± 0.5[b]	248 ± 16[b]	31 ± 2[b]
82.7	107	20 x 24 x 22.1	174.1	18.62
101.7	94.4	24 x 20 x 20.7	162.6	15.36
101.7	93.9	20 x 20 x 26.0	170.5	16.01
123.1	89.2	24 x 20 x 15.8	124.3	11.09
127.2	87.8	20 x 20 x 17.9	119.6	10.50
124.6	89.8	16 x 16 x 32.0	134.3	12.07
124.7	89.4	24 x 24 x 13.6	128.0	11.45
124.6	89.5	12 x 32 x 25.5	160.5	14.37
124.6	89.7	32 x 32 x 10.4	174.1	15.61
124.5	88.9	28 x 28 x 12.2	156.3	13.90
146.8	81.1	20 x 20 x 16.6	108.6	8.80
146.8	81.0	16 x 16 x 28.8	120.6	9.78
146.9	82.8	24 x 24 x 12.3	115.9	9.60
146.9	82.2	12 x 44 x 17.7	153.2	12.58
146.7	83.9	32 x 32 x 9.1	152.6	12.80
146.7	83.2	28 x 28 x 10.1	129.6	10.78
172.0	70.6	20 x 20 x 17.0	111.6	7.87
172.2	69.2	16 x 16 x 33.2	139.0	9.62
171.8	69.7	24 x 24 x 13.1	123.3	8.60
171.9	69.6	28 x 28 x 11.1	142.1	9.89
171.7	69.8	32 x 32 x 10.1	168.9	11.80
197.9	65.4	20 x 20 x 14.4	94.4	6.17
199.3	64.9	16 x 16 x 22.9	96.0	6.23
199.8	65.6	24 x 24 x 11.7	110.7	7.26
199.5	59.5	28 x 28 x 10.7	137.4	8.18
199.4	66.2	32 x 32 x 8.9	150.0	9.94
244.7	55.5	20 x 20 x 14.3	93.4	5.18
244.8	56.2	16 x 16 x 22.8	95.5	5.37
245.0	56.0	24 x 24 x 11.1	112.2	6.28
245.0	56.0	28 x 28 x 9.9	126.9	7.08
244.4	55.8	22 x 32 x 9.4	157.4	8.79
320.5	49.2	20 x 20 x 13.1	86.0	4.06
320.4	47.9	16 x 16 x 19.2	81.3	3.90
320.3	48.0	24 x 24 x 10.3	97.6	4.67
320.5	48.0	28 x 28 x 9.2	118.5	5.65
320.5	47.9	32 x 32 x 8.8	147.9	7.09
396.7	40.6	16 x 16 x 22.7	94.9	3.85
395.5	40.2	20 x 20 x 14.1	92.3	3.71
395.5	40.4	24 x 24 x 11.5	108.1	4.36
395.1	39.1	28 x 28 x 10.2	131.1	5.13
395.4	40.6	32 x 32 x 9.2	154.2	6.25
451.0	37.0	20 x 20 x 14.4	94.4	3.50
446.8	37.9	16 x 16 x 23.1	97.6	3.70
503.6	33.6	16 x 16 x 28.2	118.0	3.96
504.1	33.3	20 x 20 x 16.2	106.0	3.53
504.0	33.5	24 x 24 x 12.8	120.6	4.03
504.0	33.4	32 x 32 x 10.1	168.9	5.65
756.0	22.2	28 x 28 x 17.8	228.7	5.08
757.9	22.1	32 x 32 x 16.1	270.6	5.98
756.6	22.2	28 x 24 x 20.3	223.7	4.96
		Unreflected Assemblies		
124.4	89.2	24 x 24 x 28.6 ± 0.5[b]	270. ± 5[b]	24 ± 4.8[b]
146.6	83.1	24 x 24 x 24.4 ± 0.75[b]	230 ± 7[b]	27.8 ± 5.6[b]
244.6	55.5	24 x 24 x 21.2	200.4	11.13
320.2	49.1	24 x 24 x 18.8	177.3	8.71
395.0	40.6	20 x 24 x 23.8	186.7	7.58
503.5	33.3	24 x 24 x 20.8	196.2	6.54
757.0	22.1	28 x 28 x 27.7	355.6	7.87

a. $H:U^{235}$ atomic ratio is average for particular assembly.
b. Extrapolated to criticality.

Table B-3. Critical Parameters of Uranyl Fluoride Solutions
(4.89 wt% U^{235} Enriched Uranium)

H:U^{235} Concentration: H:U^{235} Atomic Ratio	H:U^{235} Concentration: g of U^{235} per cc	Container	Critical Conditions: Height (in.)	Critical Conditions: Height (cm)	Critical Conditions: Volume (liters)	Critical Conditions: U^{235} Mass (kg)
		Water-Reflected Assemblies				
524	0.04254	Aluminum Vessel 20 x 20 in. in Cross Section[a]	10.0	25.4	64.8	2.76
		20-in.-dia Stainless Steel Cylinder	11.54	29.3	59.4	2.53
		15-in.-dia Aluminum Cylinder	17.63	44.78	51.1	2.17
		15-in.-dia Stainless Steel Cylinder	19.83	50.37	57.4	2.44
		12-in.-dia Stainless Steel Cylinder	>60.0[b]	>152.5[b]	>111.2[b]	>4.73[b]
643	0.03562	30-in.-dia Aluminum Cylinder[c]	10.43	26.49	120.8	4.30
		Aluminum Vessel 20 x 20 in. Cross Section[a]	11.18	28.4	73.2	2.61
		20-in.-dia Stainless Steel Cylinder[c]	14.66	37.4	75.8	2.70
		20-in.-dia Stainless Steel Cylinder	13.67	34.7	70.3	2.50
		15-in.-dia Stainless Steel Cylinder	29.75	75.5	86.1	3.06
735	0.03179	30-in.-dia Aluminum Cylinder[c]	10.51	26.7	122.0	3.87
		Aluminum Vessel 20 x 20 in. in Cross Section[a]	12.76	32.41	82.7	2.63
		20-in.-dia Stainless Steel Cylinder[c]	16.84	42.77	86.7	2.76
		20-in.-dia Stainless Steel Cylinder	15.79	40.09	81.1	2.58
		15-in.-dia Stainless Steel Cylinder	60.24	153.01	174.4	5.54
991	0.02428	30-in.-dia Aluminum Cylinder[c]	15.94	40.49	184.7	4.48
994	0.02422	20-in.-dia Stainless Steel Cylinder[c]	35.25	89.4	181.4	4.40
		20-in.-dia Stainless Steel Cylinder	33.75	85.72	173.7	4.21
1025	0.02354	15-in.-dia Stainless Steel Cylinder	>79.6[b]	>202.2[b]	>230.5[b]	>5.42[b]
1026	0.02352	Aluminum Vessel 20 x 20 in. in Cross Section[a]	24.68	62.69	159.9	3.76
1099	0.02211	27.3-in.-dia Sphere[d]		62.5	170.5	3.77
		Unreflected Assemblies				
524	0.04254	Aluminum Vessel 20 x 20 in. in Cross Section[a]	14.12	35.9	91.6	3.89
		20-in.-dia Stainless Steel Cylinder	15.22	38.66	78.3	3.33
		15-in.-dia Stainless Steel Cylinder	>57.9[b]	>147[b]	>167.6[b]	>7.13[b]
		12-in.-dia Stainless Steel Cylinder	>60.2[b]	>152.9[b]	>111.6[b]	>4.74[b]
643	0.03562	30-in.-dia Aluminum Cylinder[e]	11.36	28.85	131.6	4.69
		Aluminum Vessel 20 x 20 in. in Cross Section[a]	15.70	39.9	101.8	3.63
		20-in.-dia Stainless Steel Cylinder	17.98	45.65	92.6	3.30
		15-in.-dia Stainless Steel Cylinder	>65.3[b]	>165.9[b]	>189.13[b]	>6.73[b]
735	0.03179	30-in.-dia Aluminum Cylinder[e]	12.40	31.50	144	4.58
		Aluminum Vessel 20 x 20 in. in Cross Section[a]	17.9	45.47	116.0	3.69
		20-in.-dia Stainless Steel Cylinder	21.43	54.35	110.1	3.50
991	0.02428	30-in.-dia Aluminum Cylinder[e]	17.62	44.75	204.1	4.96
994	0.02422	20-in.-dia Stainless Steel Cylinder	>55.0[b]	>139.7[b]	>283[b]	>6.84[b]
1002	0.02404	27.3-in.-dia Sphere[d,f]		64.60	172.0	4.14
1025	0.02354	Aluminum Vessel 20 x 20 in. in Cross Section	48-50[g]	122-127[g]	311-325[g]	7.3-7.7[g]

a. Inside measurement was 50.5 cm on a side.
b. These cylindrical volumes were subcritical. Although they were limited by the quantity of U^{235} available to the dimensions recorded, the source neutron multiplication curve indicated that they would not be critical even when extended to infinite length.
c. The top surfaces of these cylinders were not reflected.
d. The sphere was 98% filled.
e. Supported by 1-in.-thick Plexiglas table top.
f. At this concentration the sphere with a water reflector was critical when 83% filled.
g. **Extrapolated.**

Table B-4. Critical Parameters of Unreflected 37.5% U^{235} Enriched UF_4-CF_2 Assemblies

$H:U^{235}$ Atomic Ratio	Assembly Dimensions (in.)	Fuel Layer Thickness (in.)	Moderator Layer Thickness (in.)	Critical Mass (kg of U^{235}) Experimental Mass	Aluminum Base Plate Correction	Corrected Mass
0.07	29.2 x 29.2 x 29.2[a]		None	482	9.8	491.8
0.07	32.84-in.-dia x 28.0[b]		None	457.5[c]	9.8	467.3
0.165	28 x 30 x 28.14 plus 26.8 x 26.8 x 1	2	0.010[d]	467.9	9.6[e]	477.5
1.32	26 x 26 x 28-1/2 plus 2 x 4 x 1-1/16	2	1/8	325.9	5.5[e]	331.4
2.44	23 x 24 x 25-7/8	2	1/4	244.3	3.0	247.3
4.88	20 x 21-3/8 x 22-1/2 plus 7.2 x 7.2 x 1-1/8	2	1/4	153.1	1.3	154.4
4.82	21 x 22 x 20 plus 11 x 11 x 1-1/4	2	1/2	144.8	2.3	147.1
4.82	21 x 22 x 18-3/4	4	1	135.8	4.3[e]	140.1
4.74	21 x 20 x 21-1/4 plus 17 x 20 x 1-1/4	6	1-1/2	143.9	6.3[e]	150.2
7.10	19 x 20 x 19-1/4 minus 1 x 5-1/2 x 20	2	3/4	101.0	1.1[e]	102.1
10.68	17-1/2 x 18 x 17-1/2 plus 2 x 17-1/2 x 1-1/2	2	1/2	68.53	1.02	69.55
13.64	16 x 18 x 15-3/4 plus 8 x 16 x 1-3/4	1	3/4	52.70	0.95[e]	53.65
16.14	47-3/4 x 10 x 22.3 plus 47-3/4 x 2 x 1-3/8	2	3/4	110.65	0.8[e]	111.45
17.10	15 x 15-3/4 x 16-1/2 plus 1 x 15-3/4 x 8-1/2	2	3/4	43.02	0.7[e]	43.72
	Graphite-Moderated Assemblies: $C:U^{235}$ Ratio = 42.2					
Not Applicable	39 x 40 x 34-1/8 plus 6 x 24 x 4-7/8	2	2-7/8	426.7		

a. These dimensions obtained from extrapolation of source multiplication data from subcritical assemblies the largest being 28 x 28 x 28 in.

b. A pseudo-cylinder; diameter given is that of a true right cylinder of equivalent base area

c. Since this was not a true right cylinder, an error of ± 10 kg is assigned to this value.

d. Moderator was cellulose acetate sheet in this assembly only; all other assemblies employed methacrylate plastic as the moderating material.

e. Obtained by interpolation of experimental data.

Table B-5. Variation in the Critical Parameters of an Unreflected and Unmoderated 37.5% U^{235}-Enriched UF_4-CF_2 Pseudo Cylinder Induced by Various Partial Reflectors

Reflector Dimensions[a] (in.)	Change in Reactivity (cents)
IRON	
0.25 x 16 x 27	24.1
0.5 x 16 x 27	38.8
LEAD	
2 x 12 x 28	60.4
4 x 12 x 28	87.8
PARAFFIN	
1.5 x 12 x 28	102.5
3 x 12 x 28	136.6
CONCRETE BLOCKS	
6 x 8 x 30	64.3
6 x 24 x 30	155.4
UF_4-CF_2 (99.8% U^{238})	
2 x 12 x 28	65.1
4 x 12 x 28	92.8
6 x 12 x 28	103.6
UF_4-CF_2 (37.5% U^{235})	
1 x 2 x 28	8.0
2 x 12 x 28	85.0

a. The smallest dimension is the reflector thickness.

Table B-6. Critical Parameters of Water-Reflected UF_4-CF_2 Assemblies Having Average Enrichments of 37.5, 18.8, and 12.5% U^{235}

$H:U^{235}$ Atomic Ratio	Assembly Dimensions (in.)	Moderator Layer Thickness (nominal) (in.)	Critical Mass (kg of U^{235})
	37.5% U^{235} Enrichment		
0.1	22 x 23 x 19.1	None	184.6 ± 0.04
0.1	21 x 21 x 21.6	None	183.8 ± 0.06
0.1	21 x 21 x 22.0[a]	None	185.6 ± 0.4
1.3	21-1/16 x 20-5/8 x 16-7/10	1/16	130.5 ± 0.9
2.5	15-7/8 x 17 x 22-6/10	1/8	103.3 ± 3.0
5.1	15-1/2 x 17 x 14-1/2	1/4	57.7 ± 0.5
7.8	14 x 12-7/8 x 14-8/10	3/8	36.2 ± 0.5
10.7	14 x 13-1/2 x 12-2/10	1/2	28.4 ± 0.3
	18.8% U^{235} Enrichment		
0.14	36 x 36 x 34 plus 2 x 24 x 36	None	443.6
0.14	36 x 36 x 36[b]	None	452.0
0.14	36 x 36 x 36 plus 2 x 12 x 36[c]	None	460.4
8.98	20 x 21 x 17-1/2 plus 2 x 9 x 20	1/2	57.35
	12.5% U^{235} Enrichment		
3.4	36 x 36 x 38-1/4[d]	1/8	d
7.29	36 x 36 x 27 plus 2 x 12 x 18	1/4	204.8

a. Assembly protected by 1/8-in.-thick rubber sack, this experiment only; all others used 1/16-in.-thick rubber sack. Values are not corrected for effect of sack.

b. Customary 2 x 2 x 3-in. fuel modules replaced by 2 x 4 x 3-in. modules.

c. Customary 2 x 2 x 3-in. fuel modules replaced by 4 x 4 x 3-in. modules.

d. An assembly of these dimensions having a mass of 466 kg of U^{235} was subcritical, and produced a source neutron multiplication of 2.5.

Table B-7. Critical Parameters of Unreflected UF_4-CF_2 Assemblies Having Average Enrichments of 30, 25, 18.8, and 12.5% U^{235}

$H:U^{235}$ Atomic Ratio	Assembly Dimensions (in.)	Moderator Layer Thickness (in.)	Experimental Critical Mass[a] (kg U^{235})
	30% U^{235} Enrichment		
14.00	18 x 18 x 17-7/8 plus 13 x 18 x 1-5/8	5/8	59.1
	25% U^{235} Enrichment		
13.58	20 x 20 x 19-1/2 plus 12 x 20 x 1-1/2	1/2	70.5
	18.8% U^{235} Enrichment		
13.70	24 x 24 x 22 plus 2 x 24 x 1-3/8	3/4	89.3
14.57	16 x 48 x 24-1/4 plus 1 x 6 x 48	3/4	131.2
9.22	27 x 28 x 22-1/2 plus 20 x 28 x 1-1/4	1/2	136.1 (143.2)
2.45	36 x 38 x 38-1/4	1/8	472 ± 5[b]
	12.5% U^{235} Enrichment		
13.86	28 x 33 x 21-1/4 plus 15 x 28 x 1-1/4	1/2	149.5 (151.6)
13.97	24 x 48 x 30 plus 2 x 3 x 24 plus 2 x 12 x 48	1/2	185.4
7.11	39 x 40 x 40-1/2 plus 26 x 40 x 1-1/8	1/4	364.5 (370.9)

a. In general these masses have not been corrected for neutron reflection by the experimental structure and are therefore too small by 2 to 5%. In those cases where empirical corrections were made the masses are given in parentheses.

b. Estimated critical mass and size, since a partial reflector of UF_4-CF_2 blocks (uranium enriched to 0.2% U^{235}) on one face, and a top plate of 1-in.-thick aluminum were necessary to achieve criticality.

Table B.8 - Calculated Values of Buckling and Extrapolation Distance for U_3O_8-Sterotex Mixtures (4.89 wt% U^{235} Enriched Uranium)

$H:U^{235}$ Atomic Ratio	Buckling ($in.^{-2}$)	Derived Extrapolation Distance (in.) Unreflected Assemblies	Water-Reflected Assemblies
102	0.0351	0.48	3.72
124	0.0415	0.473	3.65
147	0.0435	0.461	3.55
172	0.0465	0.443	3.43
199	0.0488	0.427	3.35
245	0.0515	0.405	3.17
320	0.0556	0.382	2.93
396	0.0562	0.367	2.75
449	0.0550	0.360	2.65
503	0.0523	0.357	2.58
757	0.0361	0.354	2.33

Table B.9 - Calculated Values of Buckling and Extrapolation Distance for UO_2F_2 Solutions (4.89 wt% U^{235} Enriched Uranium)

$H:U^{235}$ Atomic Ratio	Buckling ($in.^{-2}$)	Derived Extrapolation Distance (in.)			
		Unreflected Assemblies		Water-Reflected Assemblies	
		Aluminum Container	Stainless Steel Container	Aluminum Container	Stainless Steel Container
524	0.09250	0.306	0.37	1.65	1.40
643	0.08430	0.300	0.245	1.62	1.20
735	0.07596	0.296	0.225	1.59	1.20
1025	0.05116	0.285	-	1.43	1.40

Table B.10 - Estimated Critical Dimensions of Infinitely Long Cylinders and Slabs of U_3O_8-Sterotex Mixtures (4.89 wt% U^{235} Enriched Uranium)

$H:U^{235}$ Atomic Ratio	Cylinder Diameter (in.)	Slab Thickness (in.)
	Unreflected Assemblies	
102	23.72	15.33
124	21.72	14.01
147	21.22	13.67
172	20.54	13.25
199	20.06	12.94
245	19.58	12.62
320	18.88	12.18
396	18.84	12.16
449	19.16	12.32
503	19.62	12.67
757	23.92	15.49
	Water-Reflected Assemblies	
102	18.24	9.21
124	16.32	8.1
147	15.96	8.0
172	15.44	7.7
199	15.08	7.52
245	14.86	7.5
320	14.54	7.43
396	14.78	7.75
449	15.22	8.09
503	15.88	8.68
757	20.56	11.82

Table B.11 - Estimated Critical Dimensions of Infinitely Long Cylinders and Slabs of UO_2F_2 Solutions (4.89 wt% U^{235} Enriched Uranium)

$H:U^{235}$ Atomic Ratio	Cylinder Diameter (in.)		Slab Thickness (in.)	
	Aluminum	Stainless Steel	Aluminum	Stainless Steel
		Unreflected Assemblies		
524	15.2	15.08	9.72	9.25
643	15.98	16.08	10.22	10.33
735	16.86	17.00	10.81	10.95
1025	20.68	-	13.32	-
		Water-Reflected Assemblies		
524	12.52	13.02	7.03	7.53
643	13.32	14.08	7.58	8.42
735	14.28	15.06	8.21	8.99
1000	18.40	18.46	11.02	11.08

Table B-12. Estimated Critical Conditions for U_3O_8-Sterotex Mixtures in Regular Geometries
(4.89 wt% U^{235} Enriched Uranium)

$H:U^{235}$ Atomic Ratio	Minimum Measured Critical Mass (kg of U^{235})	Sphere: Radius (in.)	Sphere: Volume (liters)	Sphere: Mass (kg of U^{235})	Equilateral Cylinder: Diameter = Height (in.)	Equilateral Cylinder: Volume (liters)	Equilateral Cylinder: Mass (kg of U^{235})	Cube: Edge (in.)	Cube: Volume (liters)	Cube: Mass (kg of U^{235})
Unreflected Assemblies										
102	-	15.8	271.2	25.6	29.5	330.5	31.2	28.0	360.	34.0
124	24[a]	14.5	208	18.6	27.3	260	23.3	25.5	270	24.1
147	27.8[a]	14.1	194	16.0	26.6	245	20.2	25.2	261	21.6
172	-	13.7	176.1	12.3	25.7	219.0	15.3	24.4	236.6	16.5
199	-	13.4	164.1	10.7	25.2	204.8	13.3	23.8	220.4	14.3
245	11.13	13.0	151.9	8.5	24.5	189.3	10.5	23.2	203.8	11.4
320	8.71	12.6	136.0	6.5	23.6	169.2	8.1	22.3	182.2	8.7
396	7.58	12.5	135.0	5.4	23.5	167.1	6.7	22.2	179.8	7.2
449	-	12.7	139.9	5.2	23.8	173.1	6.5	22.5	186.2	7.0
503	6.54	13.0	151.9	5.1	24.4	187.2	6.3	23.1	201.5	6.7
757	7.87	15.8	272.8	6.1	29.5	331.8	7.4	28.0	357.8	7.9
Water-Reflected Assemblies										
102	15.36	13.1	152.5	14.4	23.2	161.2	15.2	21.6	165.4	15.6
124	10.50	11.8	111.9	10.0	21.1	120.9	10.8	19.4	120.0	10.7
147	8.80	11.5	104.7	8.7	20.5	111.2	9.2	19.0	112.2	9.3
172	7.87	11.1	94.9	6.6	19.8	99.6	6.9	18.4	101.6	7.1
199	6.17	11.0	90.9	5.9	19.3	92.5	6.0	17.9	94.3	6.1
245	5.18	10.7	83.4	4.6	19.0	88.0	4.9	17.6	89.8	5.0
320	3.90	10.4	76.9	3.6	18.5	81.8	3.9	17.2	83.7	4.0
396	3.71	10.5	79.5	3.2	18.7	84.7	3.4	17.5	87.1	3.5
449	3.49	10.7	85.0	3.2	19.2	91.1	3.4	17.9	94.1	3.5
503	3.53	11.2	95.4	3.2	20.0	102.4	3.4	18.6	106.1	3.5
757	4.86	14.2	194.8	4.3	25.5	212.9	4.7	24.0	226.3	5.0

a. Extrapolated to criticality.

Table B-13. Estimated Critical Conditions for UO_2F_2 Solutions in Regular Geometries (4.89 wt% U^{235} Enriched Uranium)

$H:U^{235}$ Atomic Ratios	Sphere Radius (in.)	Sphere Volume (liters)	Sphere Mass (kg of U^{235})	Equilateral Cylinder Diameter (in.)	Equilateral Cylinder Volume (liters)	Equilateral Cylinder Mass (kg of U^{235})	Cube Height (in.)	Cube Volume (liters)	Cube Mass (kg of U^{235})
Unreflected Aluminum Vessels									
524	10.03	69.26	2.94	18.27	78.62	3.24	17.29	84.70	3.60
643	10.52	79.92	2.84	19.18	82.55	2.93	17.65	90.10	3.20
735	11.10	93.88	2.98	20.56	110.00	3.48	19.15	115.15	3.65
1025	13.60	172.67	4.18	24.83	197.27	4.78	23.48	212.13	5.13
Water-Reflected Aluminum Vessels									
524	8.68	44.89	1.91	15.59	48.86	2.08	14.60	51.0	2.16
643	9.20	53.44	1.90	16.57	58.45	2.08	15.01	55.42	1.97
735	9.80	64.59	2.05	17.67	71.13	2.26	16.57	74.55	2.37
1000	12.45	132.46	3.18	22.54	147.38	3.54	21.20	156.14	3.75
Unreflected Stainless Steel Vessels									
524	9.96	67.82	2.88	18.15	76.95	3.27	17.16	82.80	3.52
643	10.57	81.07	2.88	19.29	89.06	3.17	18.25	99.61	3.54
735	11.17	98.67	3.13	20.40	109.26	3.47	19.29	117.62	3.74
Water-Reflected Stainless Steel Vessels									
524	8.93	48.87	2.08	16.09	53.68	2.28	15.10	56.42	2.80
643	9.62	61.10	2.17	17.38	67.57	2.40	15.85	65.25	2.32
735	10.19	72.62	2.31	18.45	80.92	2.57	19.35	118.72	3.77
1000	12.48	133.43	3.20	22.60	148.57	3.57	21.26	157.47	3.78

Appendix C

NEUTRON FLUX MEASUREMENTS

Although the primary purpose of the work being reported was the establishment of mass and volume safety criteria, a considerable amount of data were also obtained from the various assemblies describing their behavior as nuclear chain reacting systems. The cadmium fraction was determined from a comparison of relative neutron flux distributions using bare and cadmium covered foils in the essentially homogeneous assemblies of both uranium materials enriched to 4.89% in U^{235}. A value for the extrapolation distance was obtained for the homogeneous 37.5%-U^{235}-enriched UF_4-CF_2 mixture, and neutron flux distributions were determined for units of the grossly heterogeneous 12.5 and 18.8%-U^{235}-enriched assemblies. Foil measurements in assemblies composed of the UF_4-CF_2 blocks were complicated by the contamination of unprotected foils with fission product gases escaping from the relatively porous fuel blocks. Methods of minimizing this difficulty included sealing the foils in polyvinyl chloride plastic film, placing the foils inside a sealed tube penetrating the assembly, using gold which could be chemically cleaned after exposure, and choosing a foil material of half life sufficiently long to allow decay of the short-lived surface contamination prior to counting.

The cadmium fraction, defined as that fraction of the activity produced by neutrons having energies below that of the cadmium cutoff ($\sim$ 0.5 ev), was determined at the center of U_3O_8-Sterotex assemblies of various moderations, from the smoothed curves of the relative flux distribution measured with indium* foils as detectors. The values obtained were 0.4 at an H:U^{235} atomic ratio of 200, 0.52 at H:U^{235} of 500, and 0.6 at an H:U^{235} of 756.

Flux distribution measurements in UO_2F_2 solution were also made in the 27.3-in.-dia aluminum sphere, with and without water reflector, using indium* foils, gold** foils and small uranium filled capsules.*** The cadmium fraction was 0.7 for both indium and gold and 0.94 for the U^{235} capsules. It was noted that the cadmium fraction was essentially constant near the center of the sphere.

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* The indium foils used were an alloy containing 10% indium and 90% aluminum by weight. The foils were 0.010 in. thick and 5/16 in. in diameter with an effective indium thickness of 0.0004 in. The cadmium covers were 0.02 in. thick.

** The gold foils were 0.002 in. thick and 5/16 in. in diameter.

*** The capsules, made of Plexiglas, were 1/4 in. OD by 1/4 in. long and filled with UO_2F_2 solution containing 30-40 mg of U^{235} each. The Plexiglas capsules were wrapped in 0.032-in.-thick cadmium sheet for determination of the epi-cadmium flux.

Both axial and radial flux traverses employing annular gold foils 0.002 in. thick, 1.250 in. OD by 0.500 in. ID were made in the unreflected and unmoderated psuedo-cylinder of UF_4-CF_2 blocks of 37.5% U^{235} previously described. The relative activity of these foils as a function of the distance from the center is plotted in Fig. C-1 and C-2 for the axial and radial traverses, respectively. A least-squares iteration technique using an IBM 704 was applied to obtain the best fit to an appropriate cosine or Bessel function. The bucklings determined from these measurements were then used with the actual dimensions of the assembly to obtain extrapolation distances. The axial extrapolation distance was 0.80 ± 0.05 in., with a value of 1.0 ± 0.3 in. for the radial extrapolation distance, (an uncertainty of 0.3 in. was assigned to the radius of the psuedo-cylinder). By using the sum of these buckling values (0.0308 in.$^{-2}$) with the axial extrapolation distance, a 29.4 in. cube of this material would be critical, which is in reasonable agreement with the 29.2 in. cube extrapolated from source multiplication data.

Additional information of interest in characterizing the unreflected and unmoderated 37.5% U^{235}-enriched system was obtained by the use of catcher foils. In this method, fissions occuring in U^{235} and U^{238} foils placed within the critical assembly are deduced from the fission product activity caught on aluminum foils placed in contact with the foils of fissionable material. For these experiments the uranium was in the form of 0.010-in.-thick, 1.430-in.-dia disks of either 93.3% enriched U^{235} or essentially pure U^{238} (7 ppm U^{235}), both bare and cadmium-covered. The U^{235}:U^{238} fission ratio determined by the catcher foil technique near the center of the unmoderated bare assembly was 24.3, which is in reasonable agreement with a value of 25.8 independently measured with miniature fission chambers containing thin ($\sim$100 ug/cm^2) U^{235} or U^{238} deposits. A catcher-foil measurement performed within an assembly containing the plastic moderator (H:U^{235} atomic ratio = 2.44) resulted in a U^{235}:U^{238} fission ratio of 28.8, while the fission cadmium fraction, essentially zero in the unmoderated assembly, was 0.063 in this moderated assembly. It is recognized that the surface condition of the uranium foils affects measurements of this type and absolute ratios are in error by an unknown amount.

Since flux measurements made with foils are affected by the self-shielding inherent in a foil of finite thickness, an attempt was made to estimate the importance of this effect by exposing a stack of gold and of manganese foils in the unmoderated 37.5% U^{235} assembly. The results are shown in Table C-1.

A comparison of gold and manganese foil activities gives a Au/Mn activation ratio of 14.3 for the unmoderated assembly, and a ratio of 16.7 for one with an H:U^{235} atomic ratio of 2.44.

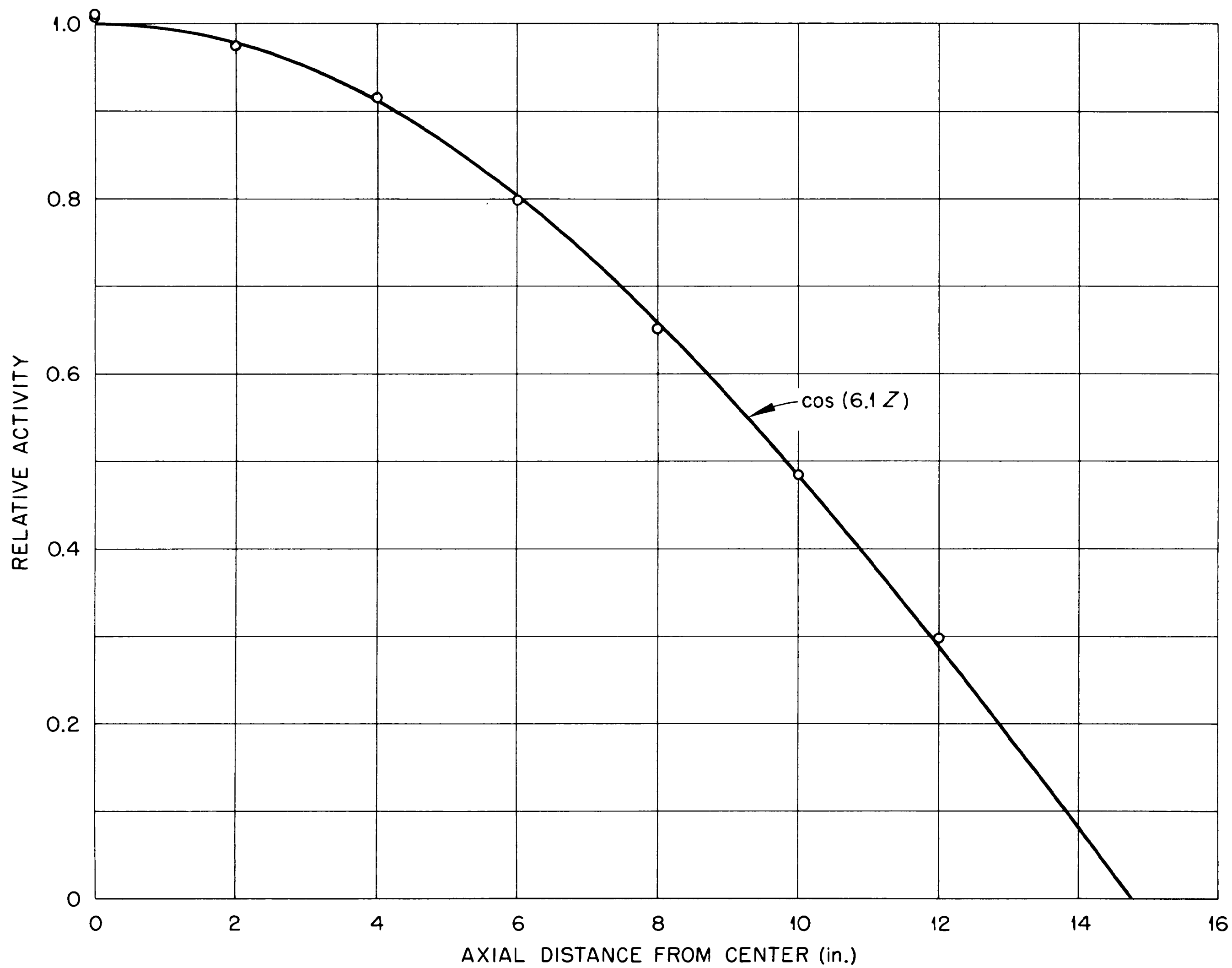

Fig. C-1. Relative Gold Foil Activity as a Function of the Axial Distance from the Center of an Unreflected and Unmoderated 37.5%-U^{235}-Enriched UF_4–CF_2 Critical Assembly.

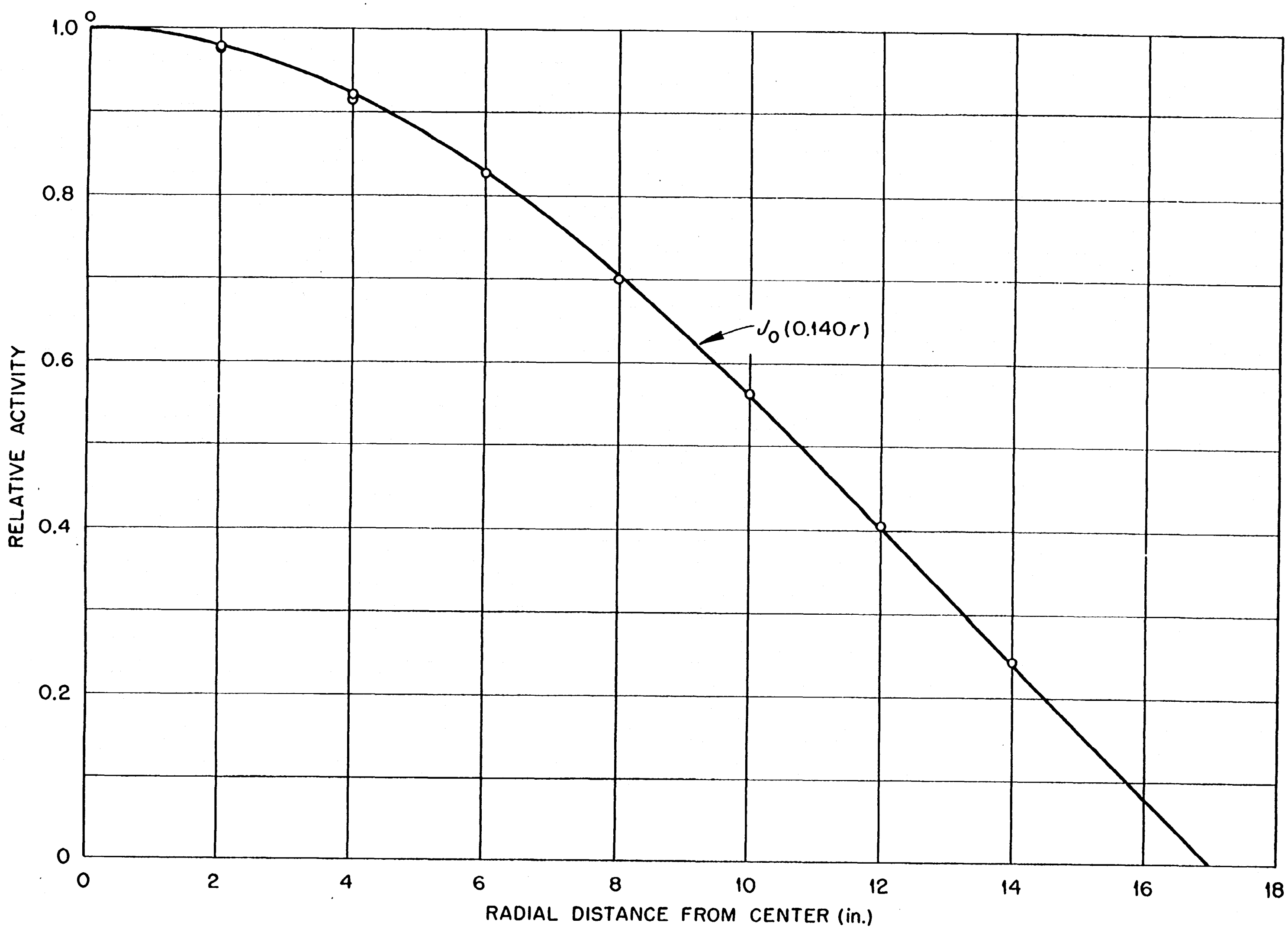

Fig. C-2. Relative Gold Foil Activity as a Function of the Radial Distance from the Center of an Unreflected and Unmoderated 37.5% U^{235}-Enriched UF_4-CF_2 Critical Assembly.

Table C-1. Relative Activities of Gold and Manganese Foils Comprising a Stack Exposed in 37.5% U^{235}-Enriched Critical Assembly

Relative Foil Position	Foil Thickness (in.)	Foil Weight (g)	Relative Activity (per g)
Annular Gold Foils: 2.00 in. OD x 0.50 in. ID			
1	0.002	1.8236	1.000
2	"	1.8209	0.972
3	"	1.7552	0.956
4	"	1.8158	0.962
5	"	1.8847	0.993
Annular Manganese Foils: 2.00 in. OD x 0.50 in. ID			
1	0.010	3.6087	1.000
2	"	3.6041	0.899
3	"	3.7831	0.988

The flux and power distributions in the 18.8%-U^{235}-enriched assemblies are of interest because of the heterogeneous distribution of both fuel and moderator. Plots of flux distribution (Fig. C-3) and of relative power distribution (Fig. C-4) in an assembly of H:U^{235} ratio of 2.45 show the anticipated large variations caused by the heterogeneity of the fuel and the moderator. A catcher-foil measurement near the center of the assembly determined the average cadmium fraction over a lattice unit to be about 0.09 and the U^{235}:U^{238} fission ratio as 37.5. An independent determination of the U^{235}:U^{238} fission ratio, made by placing miniature fission counters 9 in. from the face of the assembly, along an axis, gave a value of 58.

Gold-foil traverses were measured in directions parallel to the three axes of a parallelepiped composed of 12.5%-U^{235}-enriched UF_4-CF_2 and moderator (H:U^{235} = 7.11) to investigate this grossly inhomogeneous system. The locations of the traverses and the results are shown in Fig. C-5, C-6, and C-7. A few cadmium-covered gold foil activations were also measured and the values of the cadmium fractions are reported. The fission rate distribution along one horizontal traverse was determined by catcher foils

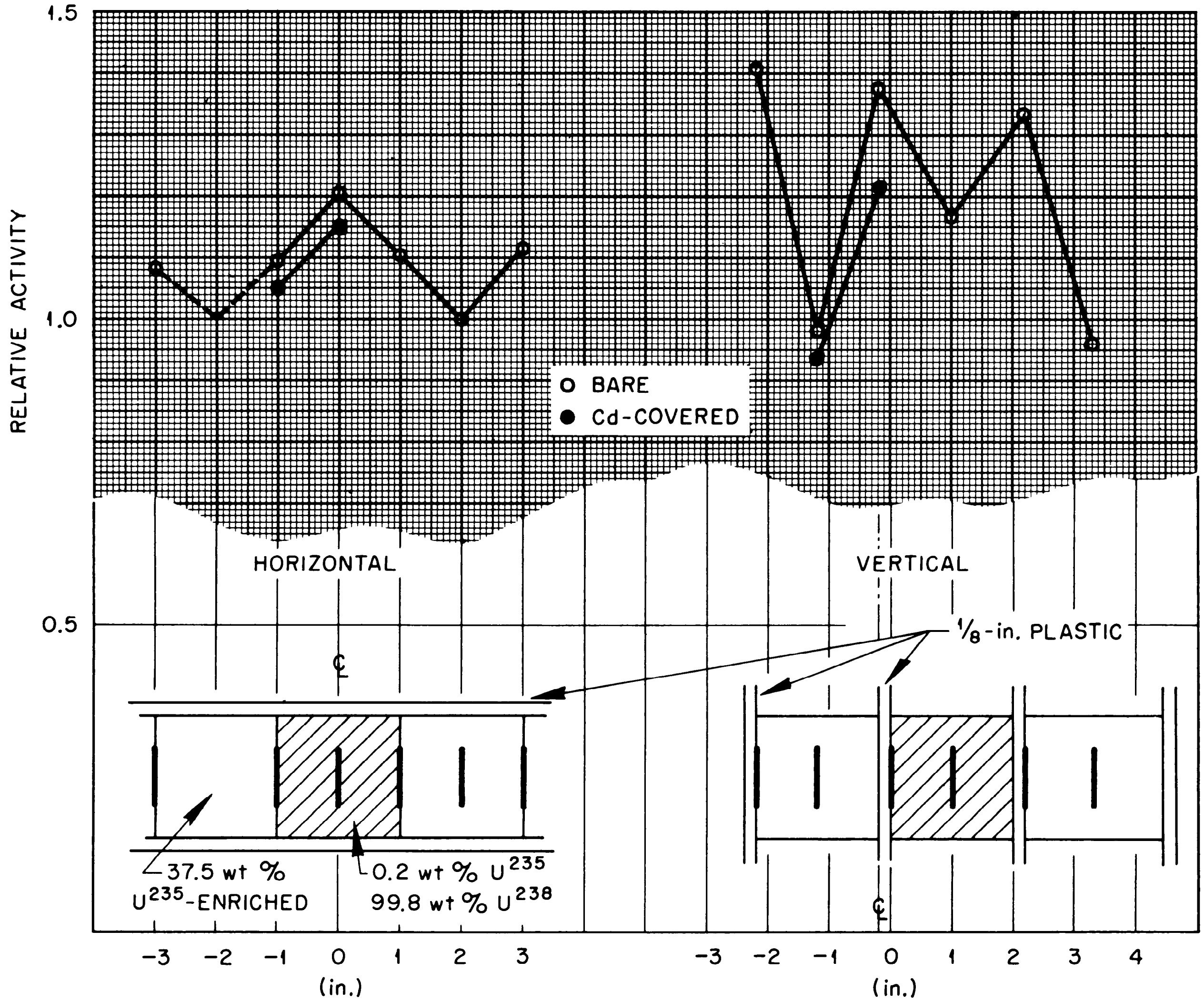

Fig. C-3. Gold Foil Traverses Through the 18.8% U^{235}-Enriched (Simulated) UF_4-CF_2 Critical Assembly, at an $H:U^{235}$ Atomic Ratio of 2.45.

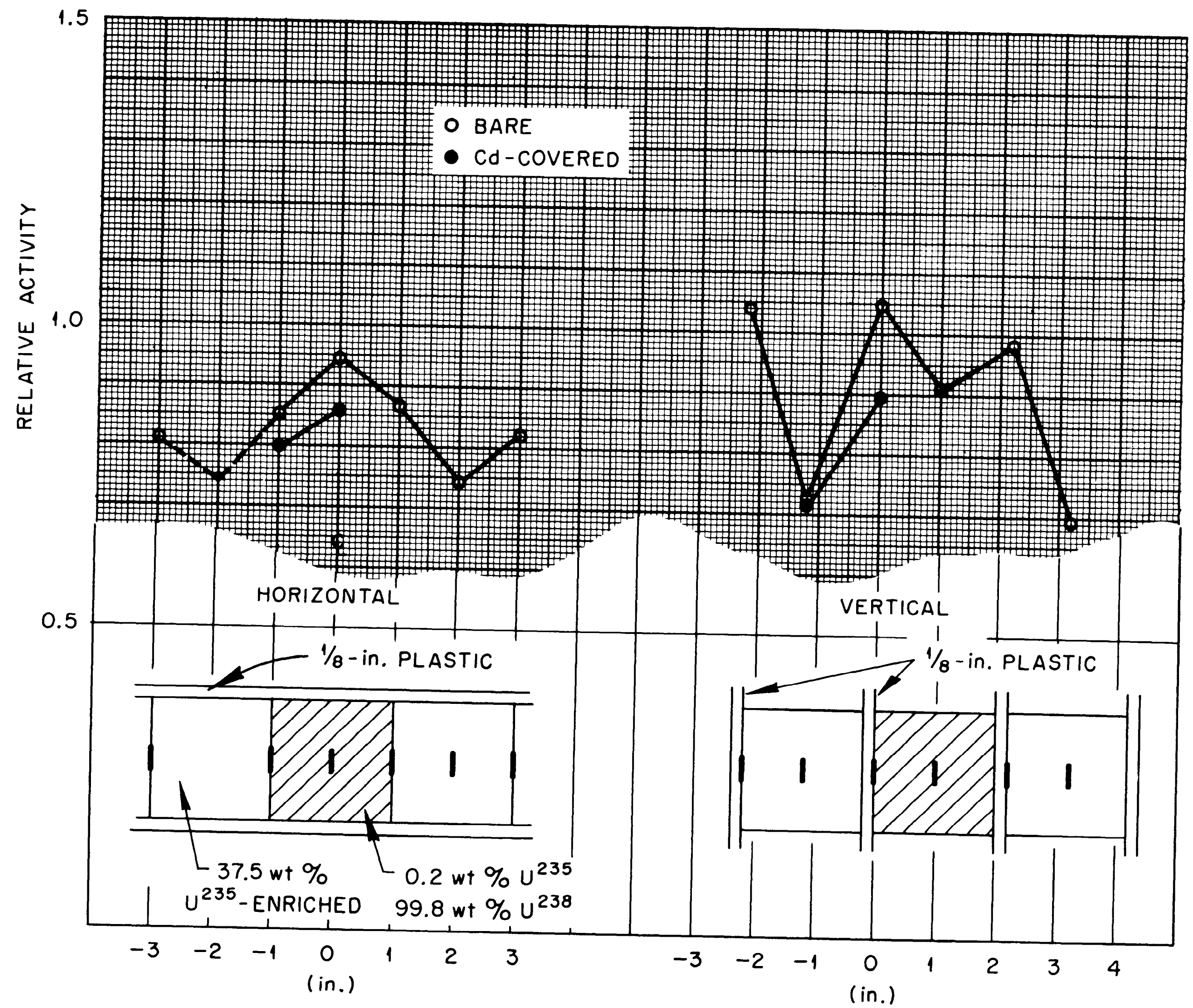

Fig. C-4. Relative Fission Rate Distributions in the 18.8% U^{235}-Enriched (Simulated) UF_4-CF_2 Critical Assembly at an $H:U^{235}$ Atomic Ratio of 2.45.

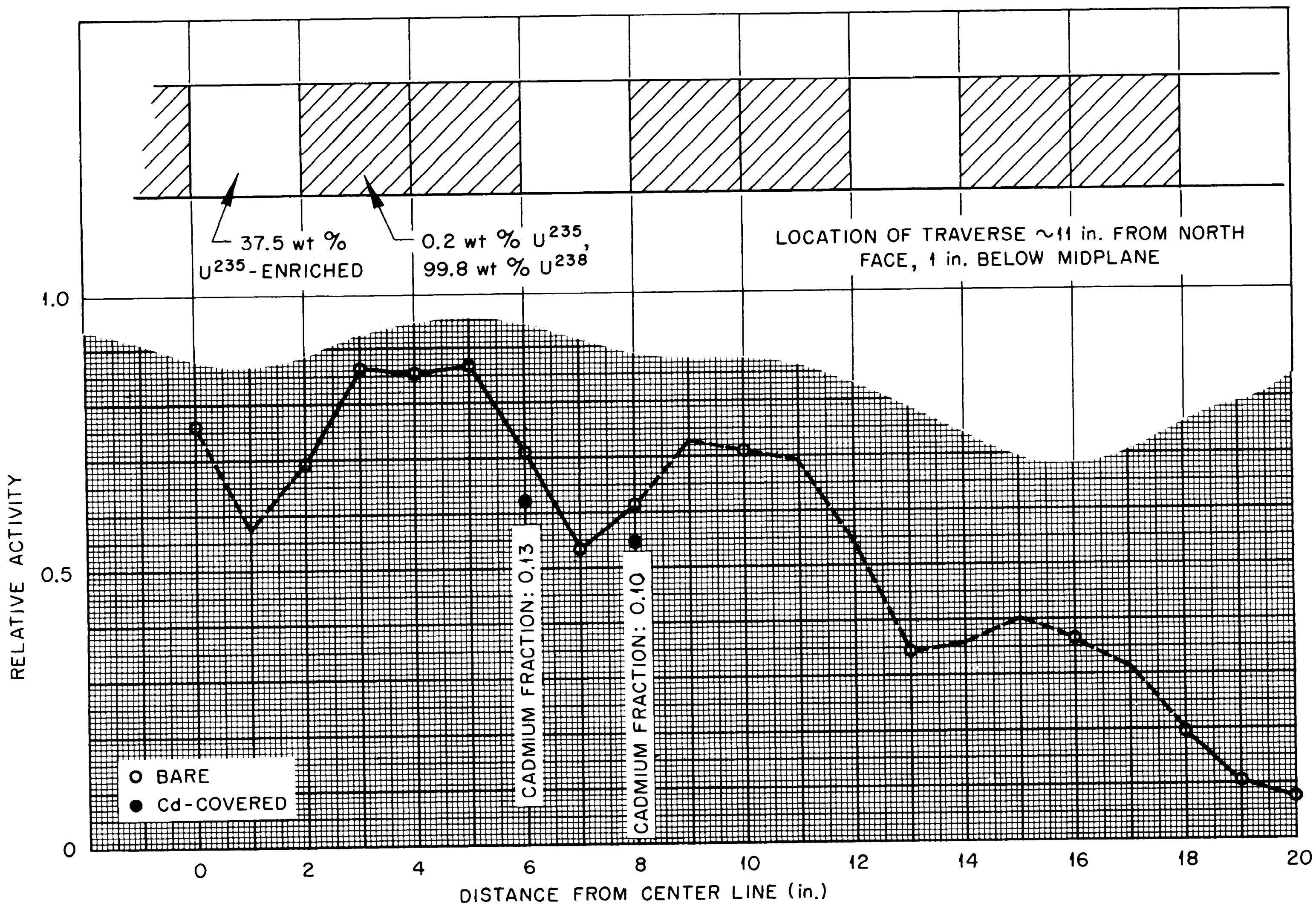

Fig. C-5. Horizontal (E-W) Gold Foil Traverse Through the 12.5% U^{235}-Enriched (Simulated) UF_4-CF_2 Critical Assembly, at an $H:U^{235}$ Atomic Ratio of 7.11.

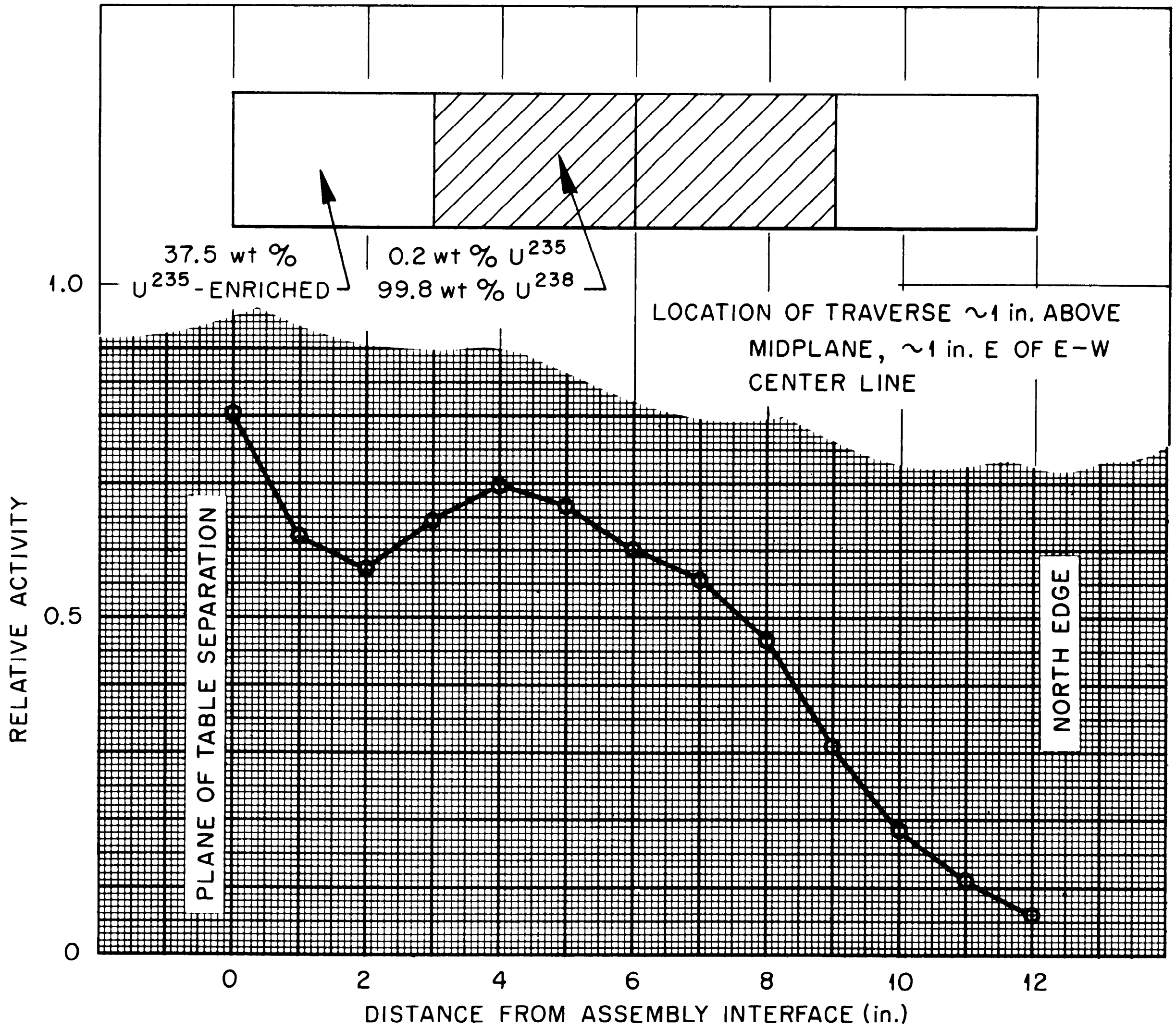

Fig. C-6. Horizontal (N-S) Gold Foil Traverse Through the 12.5 % U^{235}-Enriched (Simulated) UF_4-CF_2 Critical Assembly at an $H:U^{235}$ Atomic Ratio of 7.11.

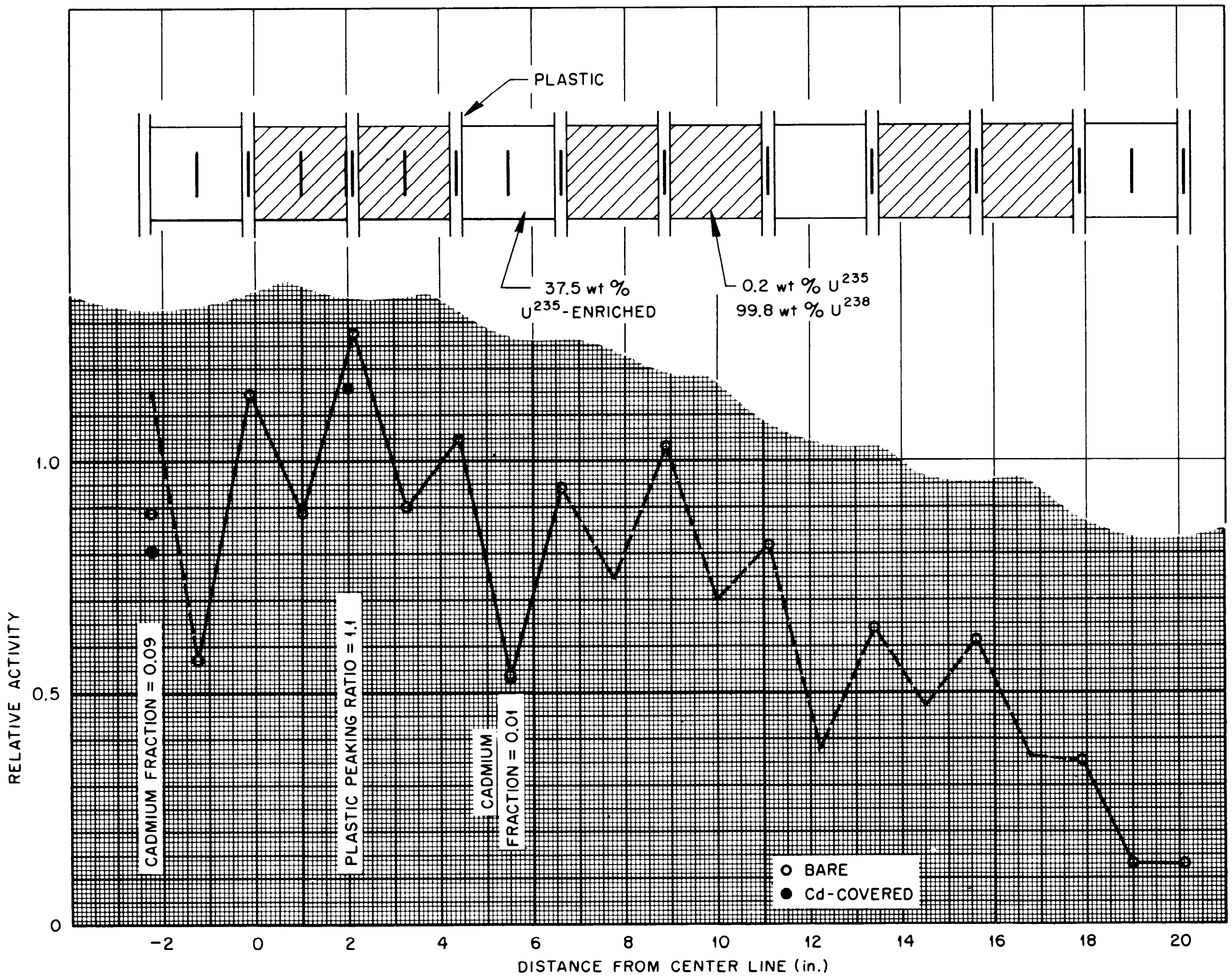

Fig. C-7. Gold Foil Traverse Vertically Through the 12.5% U^{235}-Enriched (Simulated) UF_4-CF_2 Critical Assembly at an $H:U^{235}$ Atomic Ratio of 7.11.

and is reported in Fig. C-8. The fission cadmium fraction at a point 9 in. within this assembly was 0.4. A value of 65 for the U^{235}:U^{238} fission ratio was determined by catcher-foil measurements at this point.

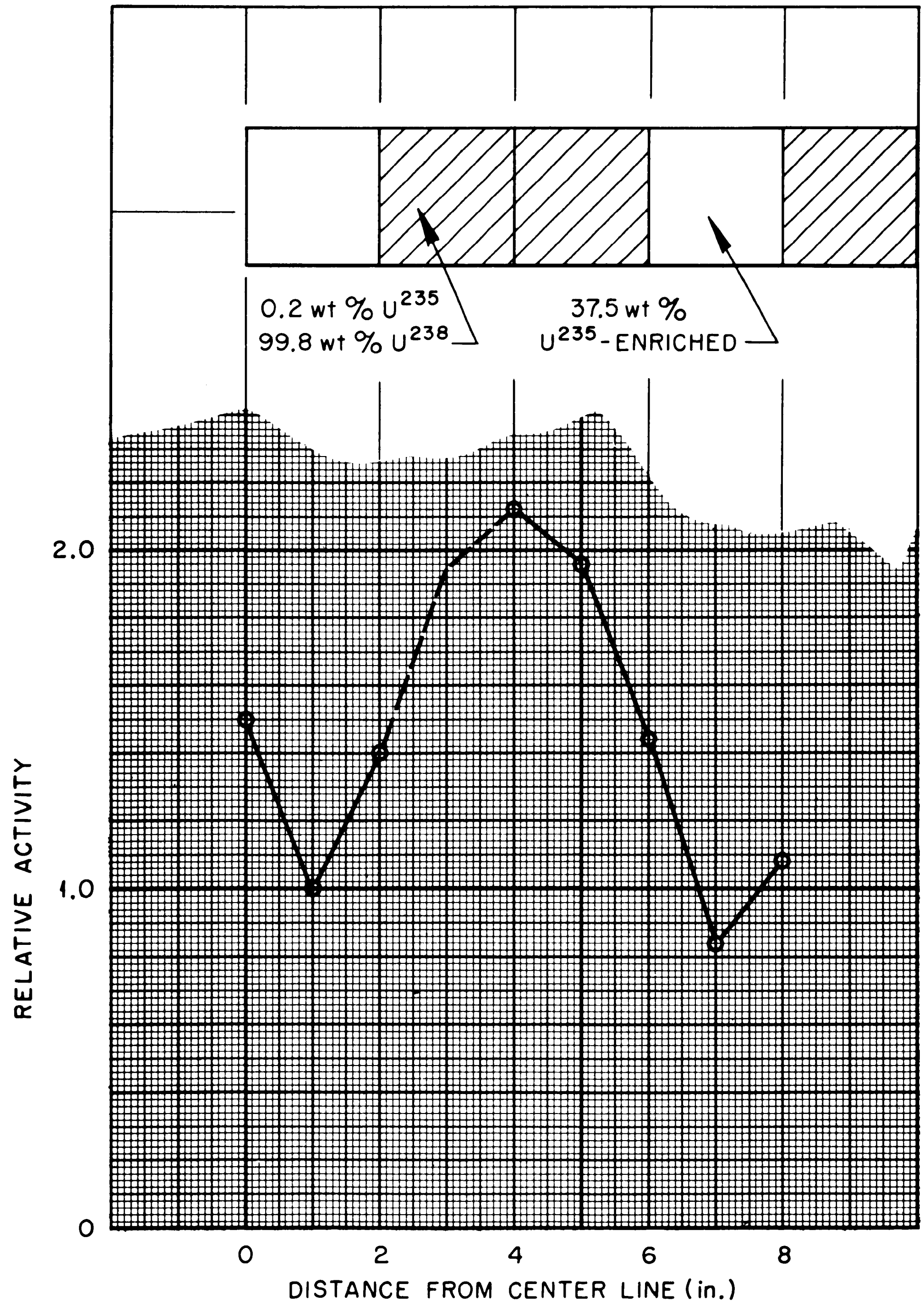

Fig. C-8 . Horizontal (E-W) Fission Rate Distribution in the 12.5% U^{235}-Enriched (Simulated) Critical Assembly, from U^{235} Foil Measurements ($H:U^{235}$ Atomic Ratio = 7.11).

Appendix D

EFFECT OF "RING TAMPING"

A series of experiments, utilizing the 4.89% U^{235}-enriched U_3O_8-Sterotex mixtures previously described, was performed to observe the effects of "ring tamping." Ring tamping may be defined as that condition in a potentially chain-reacting nuclear system wherein two or more volumes of fissionable material are surrounded by, but not separated by, a hydrogenous neutron reflector. The necessity of evaluating this condition arises from the fact that in a multicomponent nuclear system, designed to be subcritical when completely flooded by water, reliance is placed in part on the neutron absorption by the hydrogen in the water separating the components. If the separating water were removed, a hazardous condition might result.

Experiments were performed at $H:U^{235}$ atomic ratios of 103, 395, and 756, the value of 395 being very close to the optimum moderation for minimum critical mass and minimum critical volume for the enrichment studied.

The experimental procedure consisted in assembling a parallelepipedal volume of the U_3O_8-Sterotex elements sufficient to achieve criticality under three conditions: first, when completely reflected by water (the smallest mass); second, with a 16 x 16 x 24-in. air void against one face; and, finally, a nominally unreflected assembly.

Pairs of parallelepipedal assemblies, designed to permit variable separation by air-filled aluminum boxes or by a slab of water, were then constructed. The reactivity with either air or water in the gap was determined as a function of the separation distance, with criticality being achieved by varying the height of the water reflector surrounding the assembly. Where criticality could not be reached, the reactivity was determined from the source neutron multiplication. At near-optimum moderation ($H:U^{235}$ atomic ratio = 395) the mass of the system was symmetrically adjusted about the plane of separation until the assembly was critical when flooded with water.

The experimental configurations are sketched in Fig. D-1 and the experimental results are displayed in Figs. D-2, 3, 4, and 5, and given in detail in Tables D-1, 2, and 3.

For the low and intermediate $H:U^{235}$ ratios, replacement of the separating water by an equal air gap decreased the critical mass for separations between 1.5 and 12 inches. For the high moderation, one inch of water replacing a 1-in. air gap decreased the reactivity of the system from critical to a neutron multiplication of 2.

For small separations ($<$ 1.5 in.), however, the relative values of the critical masses for air and water separators appear to depend upon the degree of moderation of the fuel mixture. That is, for moderations less than optimum, the water gap, acting as a supplementary moderator, decreases the mass required

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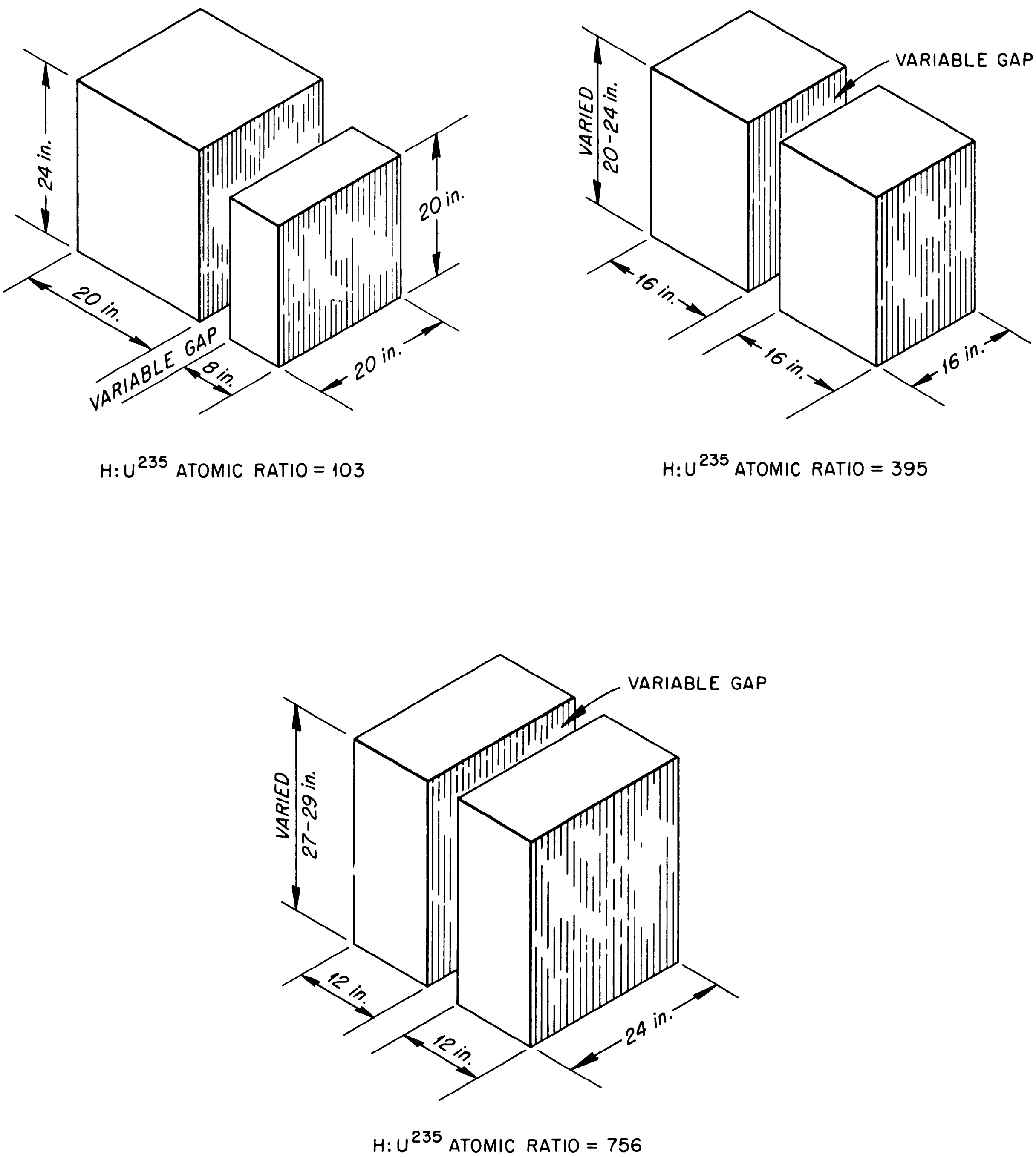

Fig. D-1. Two-Component Critical Assemblies Used in Ring-Tamping Experiments.

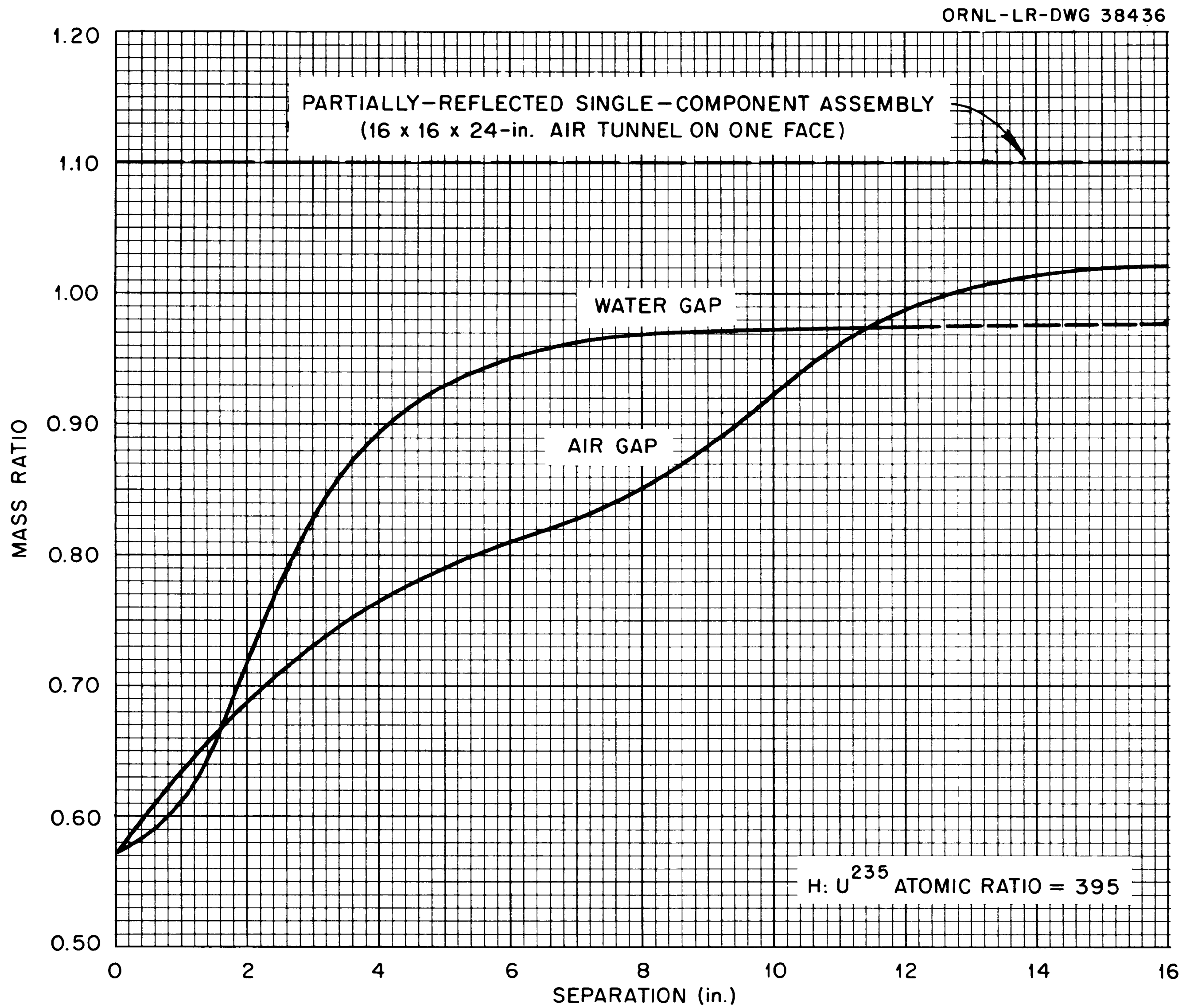

Fig. D-2. Ratio of Critical Mass per Component of Two-Component Assembly to Critical Mass of Completely-Reflected Single-Component Assembly as a Function of Separation Distance Between Components.

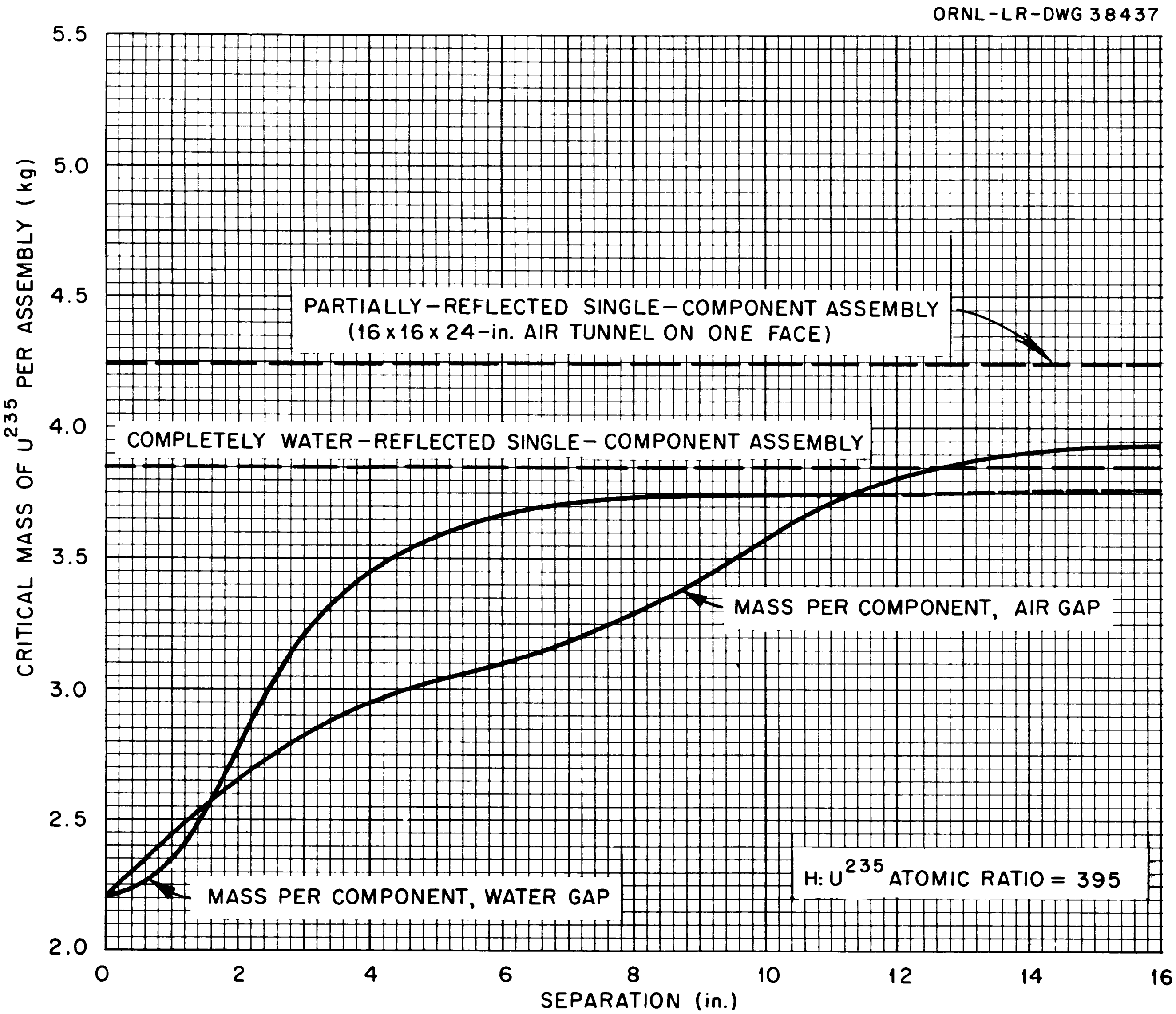

Fig. D-3. Critical Mass per Component of Single- and Two-Component Assemblies as a Function of Separation Distance Between Components.

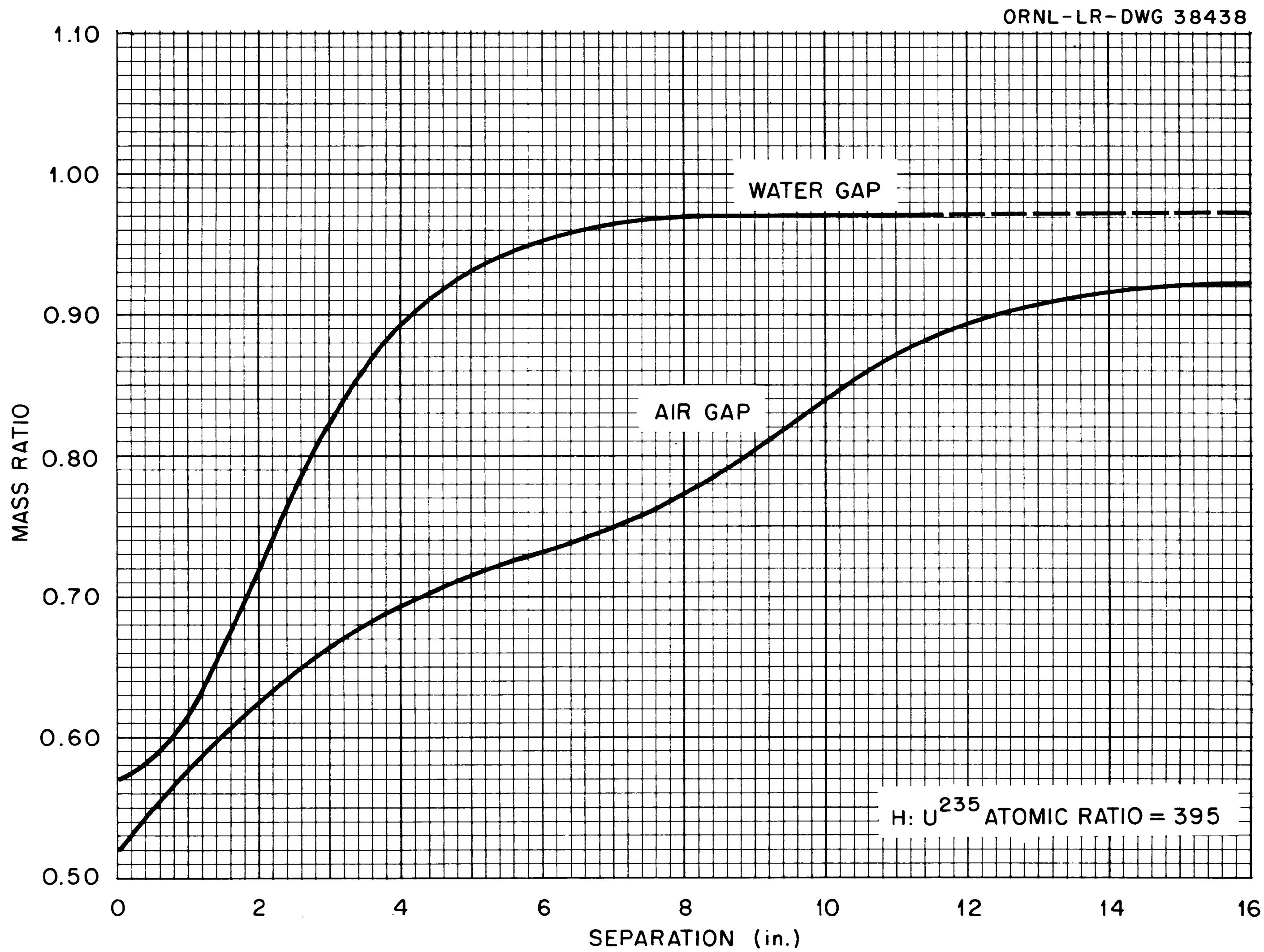

Fig. D-4. Ratio of Critical Mass per Component of Two-Component Assembly to Critical Mass of Single Component Assembly as a Function of Separation Distance Between Components. Two-Component air-gap assembly compared with partially-reflected single-component assembly; water-gap assembly with completely-reflected single component.

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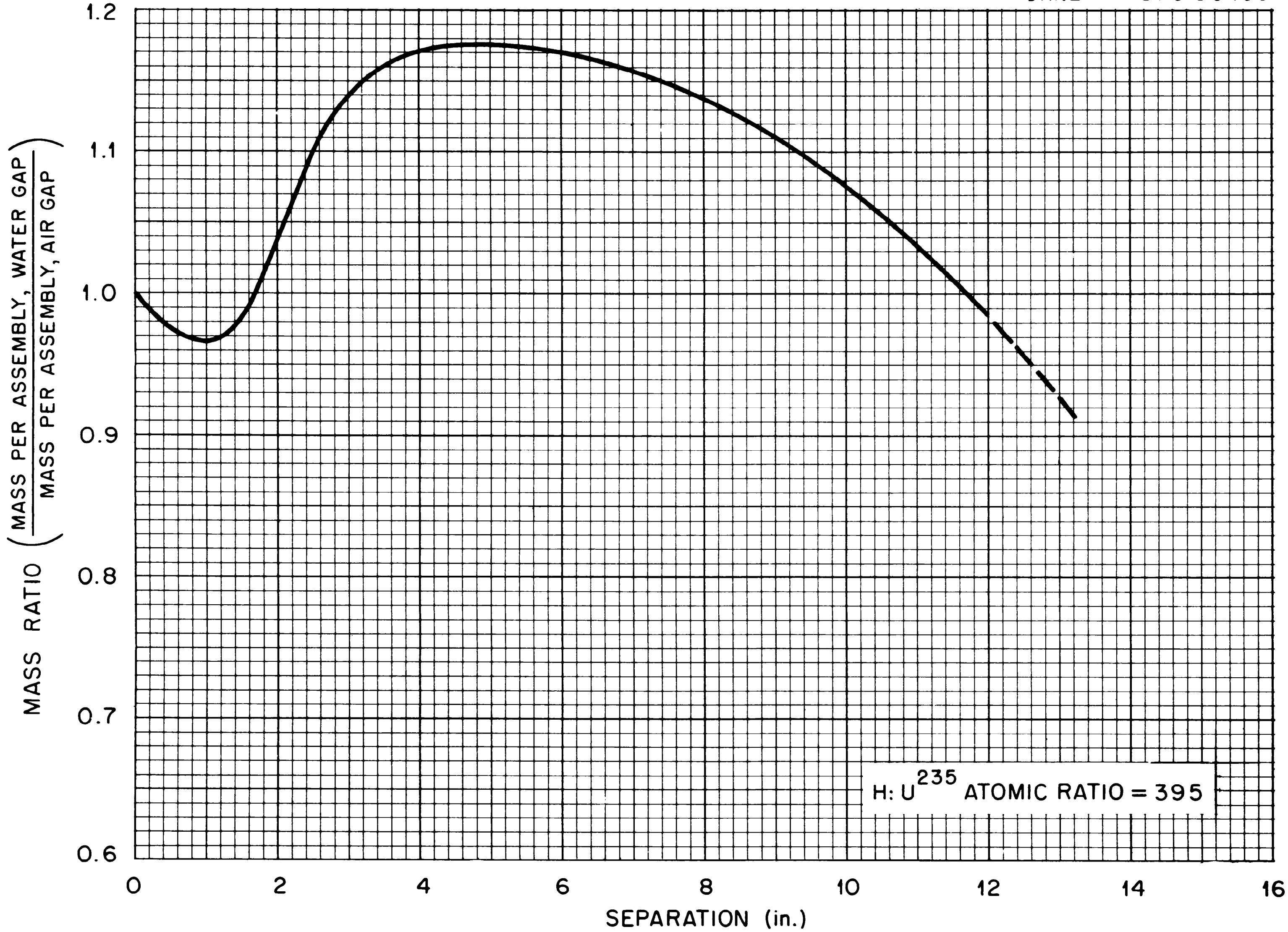

Fig. D-5. Ratio of Masses of Water-Separated and Air-Separated Assemblies as a Function of Separation Distance.

Table D-1. Critical Conditions of Two-Component Assemblies of 4.89 wt% U^{235}-Enriched U_3O_8-Sterotex Mixtures for Various Thicknesses of Air or Water Between Components

$H:U^{235}$ Atomic Ratio = 103 (Excluding water reflector-moderator)
See Fig. D-1 for Dimensions

Component Separation (in.)	Critical Mass of Assembly (kg of U^{235})		Critical Reflector Height[a] (in.)
	Air Separator	Water Separator	
1	17.74	-	22.7
1	-	17.74	20.2
2	17.74	-	26.3
2	-	17.74[b]	∞
4	25.69	-	22.7
4	-	25.69[c]	∞
8	25.69[d]	25.69[e]	∞

a. Assembly was 24 in. high referred to the same datum as reflector height measurements.
b. Not critical; source neutron multiplication = 12.0.
c. Not critical; source neutron multiplication = 3.5.
d. Not critical; source neutron multiplication = 11.1.
e. Not critical; source neutron multiplication = 2.6.

For comparison, the critical mass of a 20 x 20 in. base, single-component assembly, completely water reflected, was 14.8 kg of U^{235}; completely unreflected, 30 - 35 kg of U^{235} (extrapolated value).

Table D-2. Critical Mass of Two-Component Assembly of 4.89 wt% U^{235}-Enriched U_3O_8-Sterotex Mixtures for Various Thicknesses of Air or Water Between Components

$H:U^{235}$ Atomic Ratio = 395; Assembly Water Reflected
See Fig. D-1 for Dimensions

Component Separation (in.)	Critical Mass of Assembly (kg of U^{235})	
	Air Separator	Water Separator
0	4.40	4.40
1	4.88	4.72
2	-	5.54
4	5.88	6.88
8	6.56	7.46
12	7.60	7.48
16	7.84	-

For comparison, the critical mass of a 16 x 16-in. base, single-component assembly, completely water reflected, was 3.85 kg of U^{235}; with one face unreflected, 4.24 kg of U^{235}; and completely unreflected, 7.6 kg of U^{235}.

Table D-3. Critical Mass of Two-Component Assembly of 4.89 wt% U^{235}-Enriched U_3O_8-Sterotex Mixtures for Various Thicknesses of Air or Water Between Components

$H:U^{235}$ Atomic Ratio = 756; Assembly Water Reflected
See Fig. D-1 for Dimensions

Component Separation (in.)	Critical Mass of Assembly (kg of U^{235})	
	Air Separator	Water Separator
0	5.4	5.4
1	7.70	7.96[a]

a. Not critical; source neutron multiplication = 2.0

For comparison, the critical mass of a 12 x 24-in. base, single-component assembly, completely water reflected, was 4.8 kg of U^{235}; completely unreflected, 8.0 kg of U^{235}.

for criticality, while for moderations greater than optimum the critical mass for water separation is greater than that for air separation.

For wide gaps, ($>$ 13 in.) the critical mass per component with air separation is always greater than the critical mass of a single, isolated, completely water-reflected unit, and it may be concluded that ring tamping, or the existence of an air-filled void between two or more volumes of a water-reflected system, does not create a hazard greater than that existing under complete water flooding of any array in which the components are separated by more than 13 in.

Appendix E

LIST OF FIGURES

LIST OF FIGURES Cont'd

LIST OF FIGURES Cont'd

LIST OF TABLES

LIST OF TABLES, Cont'd

Page No.